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When It Rains, It Pours: A Case Study of Spatio-Temporal Variations in High-Intensity Precipitation Events in Arkansas

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High-Intensity Precipitation Events in Arkansas

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by

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Abstract

Climate change is having an impact on weather systems and ecosystems worldwide. Glaciers are receding, oceans are acidifying, hurricanes are stronger, and extreme precipitation is increasing in frequency. Even with the wealth of data and knowledge about the threat of climate change, some places are slow to adapt because they think that the impact to their ecosystem will not be severe. The goal of this project was to determine if climate change is having an impact on extreme precipitation in the top urban areas of Arkansas. The major concern with an increase in extreme events in urban areas is flooding. Arkansas is a landlocked state, and although some of the urban areas are centered around tributaries to the Mississippi River, frequent rainfall-induced flooding is not part of the city-subconscious when designing infrastructure. Using RClimDex, eight climate indices have been calculated to determine if climate change is having an impact on the frequency of high-intensity precipitation events. The eight indices calculated include average annual maximum temperature, average annual minimum temperature, cool days, warm days, total annual precipitation, maximum consecutive five-day precipitation amount, number of heavy precipitation days, and very wet days. A nationwide study has determined that stormwater infrastructure throughout the United States is obsolete in the face of climate change, and these indices seek to determine if there is cause for concern in Arkansas. The results indicate that for the majority of the top urban areas in Arkansas, the frequency of high-intensity precipitation events is increasing, and therefore, additional research into extreme rainfall's impact on urban flooding in Arkansas is necessary.

Acknowledgments

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Finally, I give thanks to the Lord, through Whom all things are possible.

Epigraph

"All models are wrong. Some models are useful." – George Box

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Chapter 1: Introduction

1.1 Problem Statement

The first question of twenty-three agreed upon by the hydrological scientific community is concerned with the regional acceleration and/or deceleration of the hydrological cycle due to climate change (Blöschl *et al.*, 2019). Scientists have concluded that a warmer world is a wetter world, and using the most recent projections, 94 million Americans are at high risk of extreme rainfall (Madsen and Figdor, 2007; Trenberth, 2011; Chylek *et al.*, 2017; Easterling *et al.*, 2017; Wallace-Wells, 2019; Thompson and Serkez, 2020). Current hydrologic infrastructure is not designed to withstand an increase in rainfall volume in the future, and barely suffices with the present rainfall volume (Wright, Bosma and Lopez-Cantu, 2019). If rainfall volume increases before infrastructure is updated, then cities will be unprepared for future flood scenarios. Flooding was the greatest risk to natural and anthropogenic ecosystems in the 20th century in the United States, and continues to be a significant risk in the 21st century, especially as it is aggravated by climate change (Czajkowski, Kunreuther and Michel-Kerjan, 2013; Kundzewicz *et al.*, 2014; Wing *et al.*, 2018).

1.2 Literature Review

The precedent for a study at this scale has been set by other researchers, but the most relevant study was conducted in Kansas. Extreme precipitation events were examined in Kansas, to determine if climate change had an impact on the trend in events (Rahmani and Harrington, 2018). Data was collected for 23 cities in the state of Kansas, each with over 100 years of precipitation data, and calculated five extreme precipitation indices to assess how climate change was affecting extreme precipitation events and rainfall patterns. The five indices calculated from

1890 to 2013 are the annual number of days with heavy precipitation (R10mm), maximum number of consecutive dry days (CDD), maximum consecutive five-day precipitation total (RX5day), simple daily intensity index (SDII), and very wet days (R95p). Eastern Kansas is tending towards more frequent extreme precipitation, while western Kansas is tending towards drier conditions. As such, updates are recommended for hydrologic infrastructure and water management strategies. Other recent studies have indicated an upward trend in the frequency of heavy to extreme rain events, but also noted that a common limitation of these studies was that their data started halfway through the 20th century or that their data representation was not comprehensive; or in other words, restricted to certain regions of the United States, rather than covering the entire United States (Kunkel *et al.*, 2003; Christy, 2019). However, recent digitization of pre-1948 data has allowed for more extensive analyses. The greater length of record used in this analysis establishes an important context for understanding recent changes in the United States; in other words, different qualitative conclusions are drawn from a 105-year record than from a 50-year record.

Historically, extreme rainfall statistics have been characterized by intensity-duration-frequency (IDF) curves for hydrologic infrastructure, but IDF curves do not account for rainfall nonstationarity, or rainfall that changes over time (Wright, Bosma and Lopez-Cantu, 2019). As there is a general consensus that the climate is nonstationary both in averages and extremes, if the IDF standards for the current infrastructure are outdated, then the infrastructure is unreliable (Kunkel *et al.*, 2013; Cheng and Aghakouchak, 2014). Using a timeframe that accounts for widespread urbanization and expansion of hydrologic infrastructure (1950 to 2017), data from that range was analyzed with Atlas 14 IDF estimates. Results indicated that 24-hour, 100-year rainstorms are becoming significantly more frequent, and that the 100° meridian that divides the arid West from the humid East has a role to play. Additionally, 10-year and 100-year exceedance clusters are becoming more frequent, indicating that there is an increased frequency in major storms. This indicates that there is a pressing need to update existing IDF estimates for hydrologic infrastructure design.

1.3 Areas of Interest

In order to examine the frequency of high-intensity rainfall events in urban areas of Arkansas, the top ten cities by population and then by data availability were analyzed. The top ten cities included Little Rock, Fort Smith, Fayetteville, Jonesboro, Rogers, Conway, Bentonville, Pine Bluff, Hot Springs, and Texarkana (United States Census Bureau and Arkansas Demographics by Cubit, 2018). Additional information about each city is shown in Table 1, and maps of each study location can be found in Appendix A: Study Location Maps.

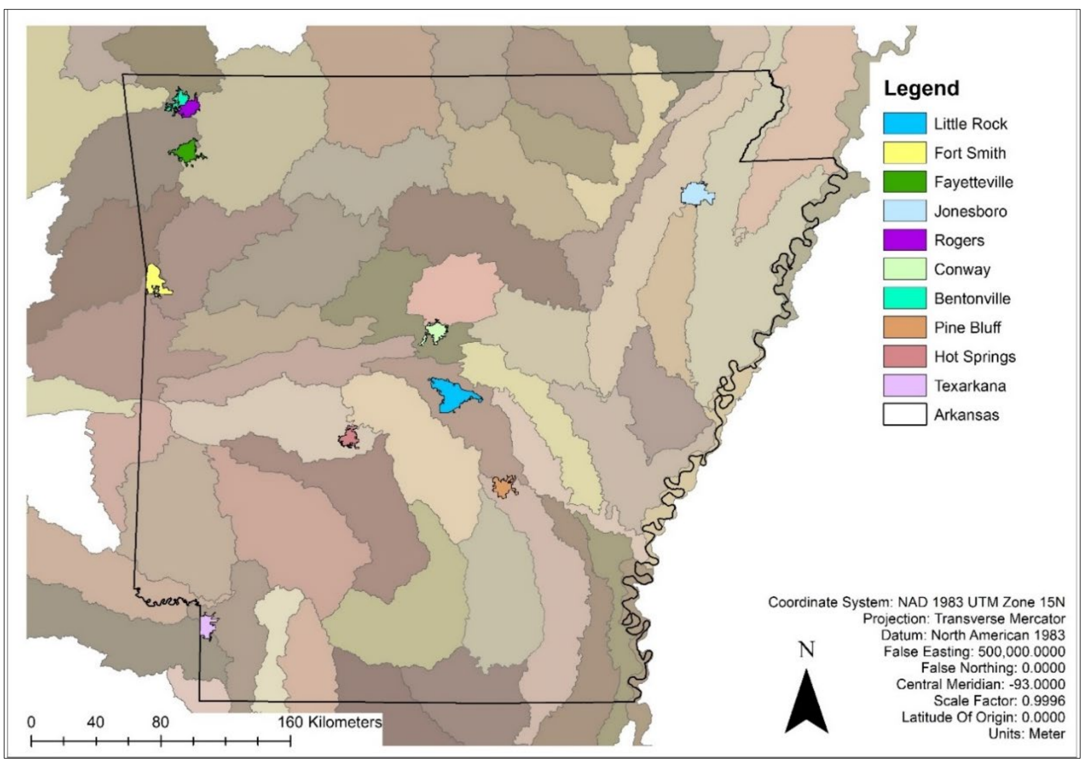

Figure 1. The location of the top ten cities by population and by data record within Arkansas and within the fifty-eight HUC-8 sub-basins of Arkansas.

The United States is divided into twenty-one major water resource regions, and two of the major water resource regions overlap with the Arkansas state boundaries (USGS, 2016). These two major water resource regions, also known as HUC-2 regions, are called the Lower Mississippi Water Resource Region and the Arkansas-White-Red Water Resource Region. Arkansas is divided into fifty-eight sub-basins, also known as HUC-8 sub-basins (Center for Advanced Spatial Technologies and Arkansas Natural Resources Commission, 2006). Each urban area is located within one to three sub-basins.

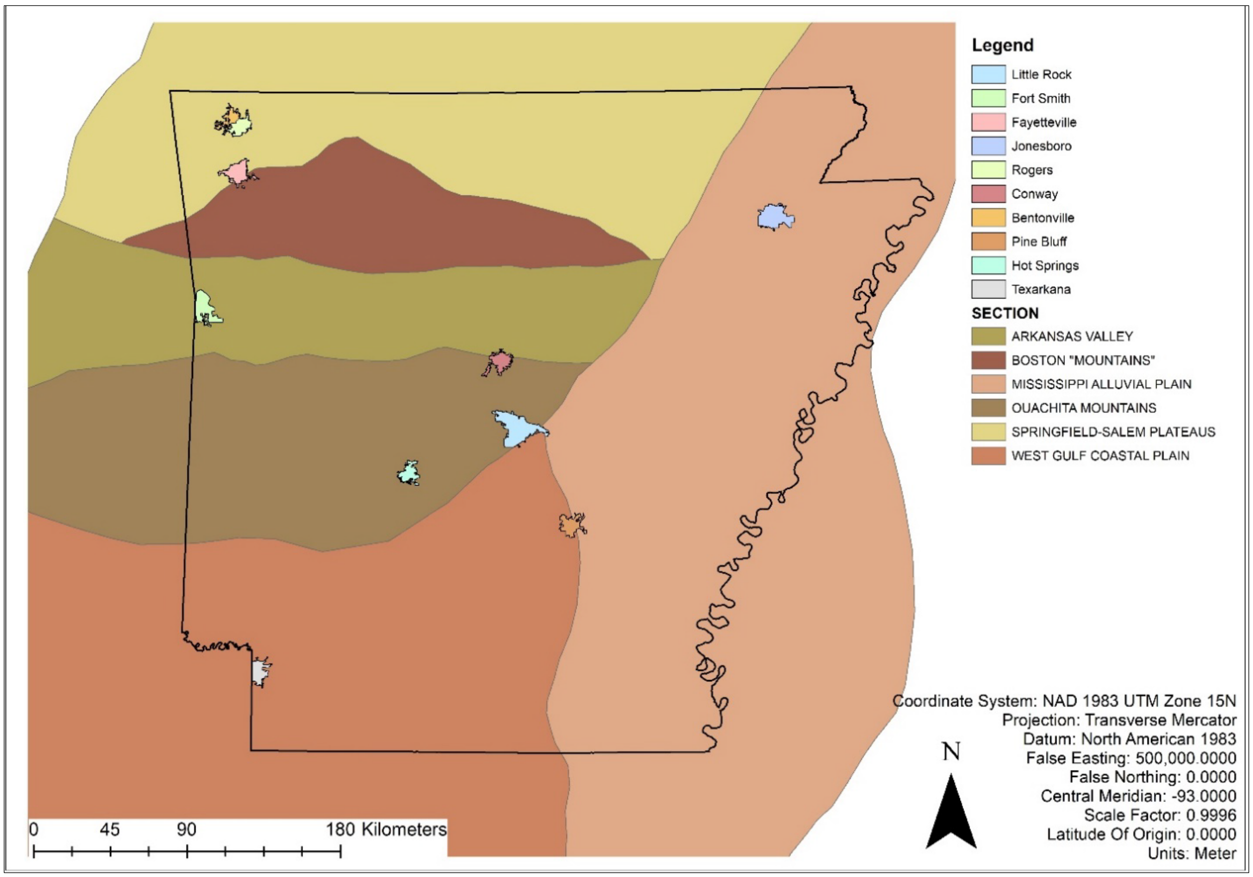

Figure 2. The location of the top ten cities by population and by data record within Arkansas and within the six physiographic regions of Arkansas.

Arkansas is divided into six physiographic regions: the Springfield-Salem Plateau, the Boston Mountains, the Arkansas River Valley, the Ouachita Mountains, the West Gulf Coastal Plain, and the Mississippi Alluvial Plain (Bragg, 2011). Some maps include Crowley's Ridge, a thin geologic formation just west of Jonesboro, as a separate physiographic region, but this map does not include it. Other maps combine the Boston Mountains and Springfield-Salem Plateau into one physiographic region called the Ozark Plateau (Arkansas Geological Survey, 2020). When examining Figure 2, a rough diagonal line can be drawn from southwest Arkansas up to northeast Arkansas on the map. That line marks the major change in topography for the state (Runkle *et al.*, 2017). The northwestern part of the state, above the line, is referred to as the Interior Highlands. The southeastern part of the state, below the line, is referred to as the Gulf Coastal Plain (Arkansas Geological Survey, 2020). Incidentally, this diagonal line also demarcates the boundary between the two major water resource regions in the state of Arkansas.

While there are six physiographic regions and two major water resource regions in the state of Arkansas, there is a single Köppen-Geiger climate classification for the entire state. The Köppen-Geiger climate classification for the state of Arkansas is Cfa, or a humid subtropical climate (Kottek, Rubel and Brugger, 2019). A humid subtropical climate is characterized by three things: warm temperate location, year-round humidity, and hot summers. The primary influencer of Arkansas' weather and climate is the Gulf of Mexico (Runkle *et al.*, 2017).

Table 1. Background information about the top ten cities in Arkansas by population and by data record.

Rank	Name	Population	Total Area (km^2)	Water Resource Region	Sub-basins (8-digit HUC)	Topographic Location	Figure no.
1	Little Rock	198,606	316.03	11	Lower Arkansas-Maumelle (11110207)	Gulf Coastal Plain	5
2	Fort Smith	88,307	176.80	11	Frog-Mulberry (11110201) Poteau (11110105) Robert S. Kerr Reservoir (11110104)	Interior Highlands	6
3	Fayetteville	85,257	143.50	11, 8	Beaver Reservoir (11010001) Illinois (11110103)	Interior Highlands	7
4	Jonesboro	75,866	208.62	8	Cache (08020302) L'Anguille (08020205) Lower St. Francis (08020203)	Gulf Coastal Plain	8
5	Rogers	66,430	99.24	11	Beaver Reservoir (11010001) Elk (11070208) Illinois (11110103)	Interior Highlands	9
6	Conway	65,782	119.67	11	Cadron (11110205) Lake Conway-Point Remove (11110203)	Interior Highlands	10
7	Bentonville	49,298	86.49	11	Elk (11070208) Illinois (11110103)	Interior Highlands	11
8	Pine Bluff	42,984	119.07	11, 8	Bayou Bartholomew (08040205) Lower Arkansas-Maumelle (11110207)	Gulf Coastal Plain	12
9	Hot Springs	38,797	97.29	8	Ouachita Headwaters (08040101) Upper Saline (08040203)	Gulf Coastal Plain	13
10	Texarkana	29,657	108.96	11	Lower Sulphur (11140302) McKinney-Posten Bayous (11140201)	Gulf Coastal Plain	14

1.4 Research Questions and Hypotheses

1.4.1 Research Questions

This study seeks to determine whether there is spatio-temporal variation in extreme precipitation for the state of Arkansas as a result of climate change. Therefore, the primary assumption under which this project operates is that climate change is real, and is happening. The first research question asks whether the frequency of high-intensity precipitation events increased in urban areas in Arkansas over a set time period, such as fifty or one hundred years. The second research question asks whether the frequency of high-intensity precipitation events increased in urban systems in Arkansas that are tied to specific physical boundaries, such as watersheds, physiographic regions, geology, or historic rainfall patterns.

1.4.2 Hypotheses

Using background information about the areas of interest, the research questions from the previous section can be reframed as testable hypotheses. The testable hypotheses of the aforementioned research questions are as follows:

1. H_{01}: The frequency of high-intensity precipitation events has not increased due to climate change in urban areas in Arkansas over the past 100+ years.
2. H_{02}: The frequency of high-intensity precipitation events has not increased due to climate change in urban areas in Arkansas that are located in the Gulf Coastal Plain.
3. H_{03}: The frequency of high-intensity precipitation events has not increased due to climate change in urban areas in Arkansas that are located in the Interior Highlands.

Chapter 2: Data and Methodology

2.1 RClimDex Overview

RClimDex is an R software program based on ClimDex, a Microsoft Excel program. ClimDex was developed by Byron Gleason at the National Climatic Data Center at NOAA in 2001 (Zhang and Yang, 2004). Xuebin Yang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada developed RClimDex in 2004, after a 2003 discovery in ClimDex resulted in data inhomogeneity that required a new interface.

RClimDex calculates twenty-seven climate indices, as recommended by the Expert Team for Climate Change Detection and Indices (Zhang and Yang, 2004). The calculation of climate indices with RClimDex requires daily climate data, such as precipitation, maximum temperature, and minimum temperature. Before the indices can be calculated, the data must go through a quality check. The quality check looks for errors, outliers, and missing data. Once the data has been checked, the indices can be computed. RClimDex requires that the input data file be an ASCII text file, so the majority of downloaded data sets have to be converted into this format. RClimDex requires that missing data be coded as -99.9, and that all data be in calendar order. An example data format is shown below.

```
1900 01 01      0       0       -6.1
1900 01 02      0       0.6     -6.7
1900 01 03      0       6.7     -8.9
1900 01 04      0       10.6    0
1900 01 05      0       14.4    5.6
1900 01 06      4.6     11.7    7.8
1900 01 07      0       12.8    8.3
1900 01 08      0       13.9    5.6
1900 01 09      7.9     15      8.9
1900 01 10      10.7    13.9    10.6
```

Figure 3. An example of the data format required for RClimDex.

The first three columns are the date, shown as Year Month Day. The fourth column is precipitation (in millimeters), the fifth is maximum temperature (in Celsius), and the sixth is minimum temperature (in Celsius).

In addition to the resolution and file specifications for RClimDex, the program itself has parameters for accurate calculations. The following parameters were used in the calculation of the results.

Table 2. RClimDex parameters for climate indices calculations.

Criteria	**Value**
Number of standard deviations for temperature	4
Upper limit for precipitation	300 mm
First year of base period *	1901
Last year of base period	2019
Latitude of data station	varies by station
Longitude of data station	varies by station
Upper threshold of daily maximum temperature	35 °C
Lower threshold of daily maximum temperature	0 °C
Upper threshold of daily minimum temperature	20 °C
Lower threshold of daily minimum temperature	0 °C
User defined threshold for daily precipitation	50 mm

* the first year is different for Bentonville, Hot Springs, and Jonesboro

Of the twenty-seven climate indices that RClimDex can calculate, eight indices have been selected for this analysis. These indices include three basic indices – the average of the annual maximum temperature (TMAXmean), the average of the annual minimum temperature (TMINmean), and total annual precipitation (PRCPTOT) – and five advanced indices – cool days (TX10p), warm days (TX90p), maximum consecutive five-day precipitation amount (RX5day), annual number of heavy precipitation days (R10mm), and very wet days (R95pTOT).

The three basic indices provide baseline data trends for the cities – average maximum temperature per year, average minimum temperature per year, and total precipitation per year. The five advanced indices break these statistics down a little further – how many warm days are there in a given year? How many cool days? What percentage of the total annual precipitation comes in heavy precipitation events?

Warm days, or TX90p, can be calculated using the following equation (Zhang, 2009).

1. $$Tx_{ij} > Tx_{in}90$$

Where:

- Tx_{ij} = daily maximum temperature on day *i* on period *j*
- $Tx_{in}90$ = calendar day 90th percentile centered on a 5-day window

Cool days, or TX10p, can be calculated using the following equation (Zhang, 2009).

2. $$Tx_{ij} < Tx_{in}10$$

Where:

- Tx_{ij} = daily maximum temperature on day *i* on period *j*
- $Tx_{in}10$ = calendar day 10th percentile centered on a 5-day window

Maximum consecutive five-day precipitation amount, or RX5day, can be calculated using the following equation (Zhang, 2009).

3. $$Rx5day_j = max\left(RR_{kj}\right)$$

Where:

- RR_{kj} = precipitation amount for the 5-day interval ending *k* for period *j*

Annual number of heavy precipitation days, or R10mm, can be calculated using the following equation (Zhang, 2009).

4. $$RR_{ij} \geq 10\ mm$$

Where:

- RR_{ij} = daily precipitation amount on day i in period j

Annual total precipitation when rainfall exceeds the 95th percentile, also known as very wet days, or R95pTOT, can be calculated using the following equation (Zhang, 2009).

5. $$R95p_j = \sum_{w=1}^{W} RR_{wj}$$

Where:

- $RR_{wj} > RR_{wn}95$
- RR_{wj} = daily precipitation amount on a wet day w (where $RR \geq 1.0$ mm) in period j
- $RR_{wn}95$ = 95th percentile of precipitation on wet days in the 1961 – 1990 period
- w = number of wet days in the period j

$RR_{wn}95$ is specific to the 1961 to 1990 period because this is a fixed variable. It compares the daily precipitation across the testing period (period j) against the climate standard determined from the 1961 to 1990 period.

Additionally, the RClimDex software program has a couple of bugs. When visualizing the climate indices, the R^2 value is always displayed one hundred times (100x) larger than the actual value, and any p-value smaller than 0.001 is always displayed as zero (0).

2.2 Data Sources

2.2.1 NOAA National Centers for Environmental Information

The National Oceanic and Atmospheric Administration's National Centers for Environmental Information (henceforth referred to as NOAA NCEI) is an online database where climate data is stored and can be retrieved via query (NOAA, 2020). The NOAA NCEI is operated by the United States government, through the Department of Commerce. The NOAA National Climatic Data Center (NCDC) was first formed in 1951 as the National Weather Records Center (NOAA, 2014). When NOAA was formed in 1970, the National Weather Records Center was incorporated into the organization and its name was changed to the National Climatic Center. The NOAA NCDC received the name National Climatic Data Center in 1982. In 2015, the NCDC was dissolved into the NCEI, along with two other data centers.

Data can be downloaded from NOAA NCEI in a variety of formats, datasets, and date ranges (NOAA, 2020). As aforementioned, RClimDex requires daily climate data, so the dataset type downloaded from NOAA NCEI was called Daily Summaries. The next search term was the date range. In order to best examine change in extreme precipitation, a long data record is needed. Therefore, data was queried from January 1, 1900 to January 1, 2020. Data can be further narrowed down by location, which can be queried by station, state, city, zip code, watershed, etc. The focus of this study is urban precipitation, so the chosen location search term was cities. However, this did not have the desired results. Only four of the ten cities could be located using this search term. Looking at the whole state by station revealed that Arkansas has 859 stations where climate data is collected. All ten cities were located by searching through the stations alphabetically. While only ten cities are included in this study, there were eighty-five potential stations for the ten cities. Each station has an estimation of coverage, where coverage is based on the most complete element in the data record. By only selecting stations that had eighty percent or greater coverage, the number of stations went from eighty-five to forty-one.

2.2.2 PRISM Climate Group

The Parameter-elevation Regressions on Independent Slopes Model Climate Group (henceforth referred to as PRISM Climate Group) is an online database where climate data is stored and can be retrieved via query (Oregon State University, 2020). The PRISM Climate Group is based at Oregon State University, and is part of the Northwest Alliance for Computational Science and Engineering, which is also based at Oregon State University. The PRISM model was first created in 1991 by an Oregon State Ph.D. student named Christopher Daly (Daly and Bryant, 2013). The Natural Resources Conservation Service became interested in the model, which advanced its development and digitization.

Data can be downloaded from the PRISM Climate Group in a variety of formats, much like the NOAA NCEI. However, daily data from PRISM Climate Group only goes back as far 1981. PRISM Climate Group has monthly climate data back to 1895, but RClimDex requires daily climate data. Therefore, PRISM data is only used to supplement NOAA NCEI data for this study.

2.3 Data Insufficiencies

When the NOAA NCEI stations were narrowed down by coverage, the number of stations went from eighty-five to forty-one. NOAA defines coverage as an approximation of total completeness based on the most complete data element, and then the overall data range (NOAA, 2020). However, this revealed that some of the cities had multi-year gaps in data coverage, or worse, hardly any data at all. It is unclear whether this lack of data is a national issue, since the data is stored and queried through a federal government site; or if it is a state issue, and there is not any allocation in the state budget to maintain the stations and update the data file. The cities with the best coverage are the capitol, the hometown of the flagship university, and a historic army town; in other words, the cities that are always the focus of studies in the state of Arkansas. But Arkansas is not homogenous, as shown by a map of its physiographic regions. To better understand how climate change is affecting extreme precipitation throughout the state, data collection needs to be improved throughout the state.

2.3.1 Rogers

When narrowed down to a data coverage of eighty percent or greater, Rogers was left with four data stations. Three of the four stations have records shorter than five years.

Table 3. Rogers NOAA NCEI NCDC stations with 80% or greater coverage.

Station Name	Station ID	Start Date	End Date	Coverage	Notes
Rogers 2.4 SSW, AR	US1ARBT0050	2/19/2017	10/20/2020	98%	
Rogers 3.4 NNE, AR	US1ARBT0035	4/8/2013	11/25/2014	87%	3 year gap in Rogers data (2014 to 2017)
Rogers 3.8 SW, AR	US1ARBT0024	6/1/2012	1/10/2014	84%	
Rogers, AR	USC00036248	1/1/1892	2/28/1975	97%	37 year gap in Rogers data (1975 to 2012)

While there is a thirty-seven-year gap between two of the stations, this gap can be mostly overcome using data from PRISM Climate Group; 1975 to 1981 is only a six-year gap, from which is easier to extrapolate.

Chapter 3: Results

3.1 Overview

The following table shows the finalized set of stations and datasets that were downloaded and analyzed for this study.

Table 4. List of data stations and datasets downloaded for analysis.

Station Name	From	Start *	End *	Notes
Bentonville 4 S, AR US	NOAA	6/1/1943	12/31/1980	366 missing values from 1943 to 1980
Bentonville, AR (36.32194, -94.215)	PRISM	1/1/1981	1/1/2020	
Conway, AR US	NOAA	1/1/1900 1/1/2010	1/1/1990 1/1/2020	481 missing values from 1900 to 1990; 72 from 2010 to 2020
Conway, AR (35.1034, -92.4903)	PRISM	1/1/1990	1/1/2010	
Fayetteville Experimental Station, AR US	NOAA	1/1/1900	1/1/2000	585 missing values from 1900 to 2000
Fayetteville, AR (36.1010, -94.1736)	NOAA	1/1/2000	1/1/2020	
Fort Smith, AR US	NOAA	10/1/1900	9/26/1945	21 missing values from 1900 to 1945
Fort Smith Regional Airport, AR US	NOAA	9/27/1945	1/1/2020	17 missing values from 1945 to 2020
Hot Springs 1 NNE, AR US	NOAA	1/1/1930	12/31/1980	774 missing values from 1930 to 1980
Hot Springs, AR (34.5129, -93.0487)	PRISM	1/1/1981	1/1/2020	
Jonesboro 2 NE, AR US	NOAA	1/1/1910	1/1/2000	437 missing values from 1910 to 2000
Jonesboro Municipal Airport, AR US	NOAA	1/1/2000	1/1/2020	68 missing values from 2000 to 2020
Little Rock State Capitol, AR US	NOAA	1/1/1900	1/1/1940	
Little Rock Airport Adams Field, AR US	NOAA	1/1/1940	1/1/2020	42 missing values from 1940 to 1950
Pine Bluff, AR US	NOAA	1/1/1900 1/1/1980	9/30/1948 1/1/1990	71 missing values from 1900 to 1948; 9 from 1980 to 1990

Table 4. (cont.)

Station Name	From	Start *	End *	Notes
Pine Bluff Grider Field, AR US	NOAA	10/1/1948 1/1/1990	1/1/1980 1/1/2020	174 missing values from 1948 to 1980, 1990 to 2020
Rogers, AR US	NOAA	1/1/1900	1/1/1975	548 missing values from 1900 to 1975
Rogers, AR (36.36667, -94.1)	PRISM	1/1/1981	1/1/2020	
Texarkana Webb Field, AR US	NOAA	1/1/1900	12/31/1980	814 missing values from 1900 to 1980
Texarkana, AR (33.456, -93.9878)	PRISM	1/1/1981	1/1/2020	
*** dates listed as mm/dd/yyyy**				

The results of the RClimDex analyses are shown here in overview, but are broken down by individual city in the following sections. An alpha value, or significance level, of 0.10 was used for determining statistical significance of the results.

Table 5. P-Values for Results of Significance for full data record, with α = 0.10.

	TMAX	TMIN	TX90p	TX10p	PRCPTOT	RX5day	R10mm	R95p
Little Rock	≤0.001	0.01	≤0.001	≤0.001	0.012	---	0.009	0.012
Fort Smith	≤0.001	0.012	0.063	≤0.001	≤0.001	0.009	≤0.001	0.003
Fayetteville	≤0.001	---	≤0.001	≤0.001	---	0.048	---	---
Jonesboro	≤0.001	0.001	≤0.001	≤0.001	---	---	---	---
Rogers	≤0.001	---	N/A	N/A	0.036	0.087	0.058	---
Conway	≤0.001	---	≤0.001	0.005	---	---	---	---
Bentonville	0.003	≤0.001	0.016	0.004	---	0.073	---	---
Pine Bluff	≤0.001	0.007	≤0.001	0.005	---	---	---	---
Hot Springs	≤0.001	≤0.001	0.006	≤0.001	---	---	---	---
Texarkana	≤0.001	0.051	≤0.001	≤0.001	---	---	---	---

Table 6. P-Values for Results of Non-Significance for full data record, with α = 0.10.

	TMAX	TMIN	TX90p	TX10p	PRCPTOT	RX5day	R10mm	R95p
Little Rock	---	---	---	---	---	0.619	---	---
Fort Smith	---	---	---	---	---	---	---	---
Fayetteville	---	0.193	---	---	0.266	---	0.282	0.403
Jonesboro	---	---	---	---	0.505	0.9	0.805	0.68
Rogers	---	0.949	N/A	N/A	---	---	---	0.952
Conway	---	0.146	---	---	0.344	0.823	0.261	0.353
Bentonville	---	---	---	---	0.137	---	0.194	0.265
Pine Bluff	---	---	---	---	0.755	0.211	0.524	0.797
Hot Springs	---	---	---	---	0.981	0.386	0.218	0.405
Texarkana	---	---	---	---	0.335	0.666	0.138	0.128

Interestingly, the larger cities have a higher amount of statistically significant results. Rogers shows a p-value of N/A for TX90p and TX10p in both Tables 5 and 6, because these indices could not be calculated due to the percentage of data that was missing from the full record.

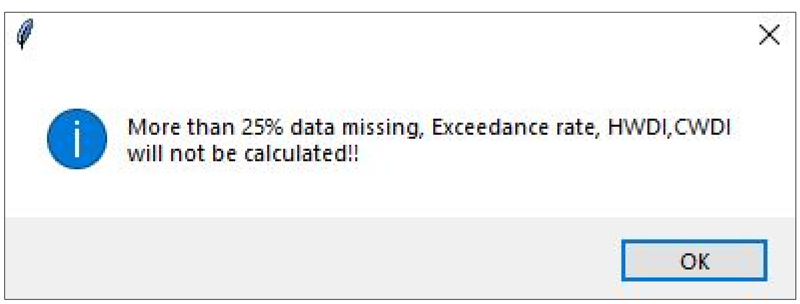

Figure 4. RClimDex error message shown for the Rogers data analysis.

Having shown which results are significant and which results are not significant, the following table shows the trends of the significant results.

Table 7. Slope Values for Results of Significance for the full data record.

	TMAX	TMIN	TX90p	TX10p	PRCPTOT	RX5day	R10mm	R95p
Little Rock	0.012	-0.005	0.05	-0.051	1.639	---	0.046	1.16
Fort Smith	0.009	-0.006	0.026	-0.036	2.819	0.338	0.074	1.719
Fayetteville	-0.014	---	-0.055	0.048	---	0.273	---	---
Jonesboro	-0.016	0.009	-0.088	0.03	---	---	---	---
Rogers	-0.014	---	N/A	N/A	1.529	0.258	0.041	---
Conway	-0.01	---	-0.057	0.028	---	---	---	---
Bentonville	-0.016	0.019	-0.078	0.058	---	0.526	---	---
Pine Bluff	-0.013	0.006	-0.08	0.027	---	---	---	---
Hot Springs	-0.016	-0.018	-0.067	0.062	---	---	---	---
Texarkana	-0.013	0.004	-0.068	0.038	---	---	---	---

Generally, the trends in Table 7 are one of two ways – either a very slow decrease, or a steady to strong increase. The majority of the temperature results show a very slow decrease, while all of the precipitation indices show a steady to strong increase. Graphs of the trends shown in Table 7 can be found in Appendix C: Additional Graphs. Five of the cities – Jonesboro, Conway, Pine Bluff, Hot Springs, and Texarkana – do not have statistically significant results for any of the precipitation indices for the full data record. In the following sections, each city is broken down into smaller intervals, ranging from seventeen to forty years, and analyzed as shorter time periods. While the five aforementioned cities may not have statistically significant results for the full data record, the intervals within the full data record may have statistically significant results.

3.2 Little Rock

Little Rock's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, and 1990 – 2020). The following table shows results of both significance and non-significance.

Table 8. P-values for Little Rock results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.168	0.36	0.679	0.52
TMIN	0.01 **	0.62	0.07 *	0.011 **	0.322
TX90p	≤0.001 **	0.107	0.23	0.545	0.469
TX10p	≤0.001 **	0.867	0.379	0.842	0.908
PRCPTOT	0.012 **	0.885	0.104	0.082 *	0.148
RX5day	0.619	0.572	0.741	0.485	0.062 *
R10mm	0.009 **	0.747	0.074 *	0.118	0.928
R95p	0.012 **	0.61	0.455	0.4	0.084 *

Seven of the eight climate indices are statistically significant for the full data record, with maximum consecutive five-day precipitation amount as the only non-significant index. All seven of those indices are significant at the 95% confidence level. Only one other index is statistically significant at the 95% confidence level, and it is the average annual minimum temperature for the 1960 to 1990 interval. Five other indices are significant at the 90% confidence level, and they are the average annual maximum temperature for the 1930 to 1960 interval, the annual number of heavy precipitation days for the 1930 to 1960 interval, the total annual precipitation amount for the 1960 to 1990 interval, the maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, and the very wet days for the 1990 to 2020 interval.

The average annual minimum temperature has the highest number of significant results, with three significant trends: the full data record, the 1930 to 1960 interval, and the 1960 to 1990 interval. The only index that isn't statistically significant for the full data record is statistically significant at the 90% confidence level for the 1990 to 2020 interval, and that index is the maximum consecutive five-day precipitation amount.

Table 9. Slope values for Little Rock results of significance. (parentheses) denotes a result that's a few hundredths larger than α = 0.10.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	0.012	---	---	---	---
TMIN	-0.005	---	-0.027	0.03	---
TX90p	0.05	(0.159)	---	---	---
TX10p	-0.051	---	---	---	---
PRCPTOT	1.639	---	(7.507)	9.005	---
RX5day	---	---	---	---	1.782
R10mm	0.046	---	0.254	---	---
R95p	1.16	---	---	---	7.746

Overall, the trends shown in Table 9 indicate an increase in most indices. The only negative trends are for average annual minimum temperature and cool days. The strongest increasing trends are total annual precipitation, with very wet days having the second-strongest increasing trends.

3.3 Fort Smith

Fort Smith's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, 1990 – 2020). The following table shows results of both significance and non-significance.

Table 10. P-values for Fort Smith results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.462	0.853	0.528	0.076 *
TMIN	0.012 **	0.046 **	≤0.001 **	0.779	0.001 **
TX90p	0.063 *	0.197	0.85	0.657	0.196
TX10p	≤0.001 **	0.491	0.241	0.772	0.057 *
PRPCTOT	≤0.001 **	0.126	0.319	0.299	0.755
RX5day	0.009 **	0.196	0.805	0.25	0.431
R10mm	≤0.001 **	0.194	0.208	0.297	0.437
R95p	0.003 **	0.083 *	0.572	0.99	0.093 *

All eight of the climate indices are statistically significant for the full data record. Seven of the eight are statistically significant at the 95% confidence level, and the eighth is statistically significant at the 90% confidence level. Three additional results are statistically significant at the 95% confidence level, and they are the average annual minimum temperature at the 1900 to 1930 interval, at the 1930 to 1960 interval, and at the 1990 to 2020 interval. Four additional results are statistically significant at the 90% confidence level. Those results are very wet days on the 1900 to 1930 interval, average annual maximum temperature on the 1990 to 2020 interval, cool days on the 1990 to 2020 interval, and very wet days on the 1990 to 2020 interval.

The average annual minimum temperature has the highest number of statistically significant results, with four significant trends: the full data record, the 1900 to 1930 interval, the 1930 to 1960 interval, and the 1990 to 2020 interval.

Table 11. Slope values for Fort Smith results of significance.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	0.009	---	---	---	0.037
TMIN	-0.006	0.026	-0.076	---	0.044
TX90p	0.026	---	---	---	---
TX10p	-0.036	---	---	---	-0.137
PRPCTOT	2.819	---	---	---	---
RX5day	0.338	---	---	---	---
R10mm	0.074	---	---	---	---
R95p	1.719	5.378	---	---	7.034

Overall, the trends shown in Table 11 indicate an increase in most indices. The only negative trends are for average annual minimum temperature and cool days. The strongest increasing trends are very wet days on the 1900 to 1930 interval and on the 1990 to 2020 interval, but the strongest increasing trend for the full data record is total annual precipitation amount.

3.4 Fayetteville

Fayetteville's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, and 1990 – 2020). The following table shows results of both significance and non-significance.

Table 12. P-values for Fayetteville results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.312	0.24	0.011 **	0.939
TMIN	0.193	0.312	≤0.001 **	0.067 *	0.518
TX90p	≤0.001 **	0.5	0.402	0.816	0.846
TX10p	≤0.001 **	0.642	0.832	0.005 **	0.704
PRCPTOT	0.266	0.729	0.87	0.542	0.843
RX5day	0.048 **	0.401	0.683	0.281	0.102
R10mm	0.923	0.958	0.42	0.193	0.981
R95p	0.403	0.12	0.834	0.4	0.515

Only half of the climate indices are statistically significant for the full data record, and those are average annual maximum temperature, warm days, cool days, and maximum consecutive five-day precipitation amount. All four of the indices that are statistically significant for the full data record are statistically significant at the 95% confidence level. Four additional results are statistically significant. The three that are statistically significant at the 95% level are average annual minimum temperature for the 1930 to 1960 interval, average annual maximum temperature for the 1960 to 1990 interval, and cool days for the 1960 to 1990 interval. The one that is statistically significant at the 90% confidence level is average annual minimum temperature for the 1960 to 1990 interval.

Table 13. Slope values for Fayetteville results of significance. (parentheses) denotes a result that's a few hundredths larger than α = 0.10.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	-0.014	---	---	-0.041	---
TMIN	---	---	-0.068	-0.026	---
TX90p	-0.055	---	---	---	---
TX10p	0.048	---	---	0.214	---
PRCPTOT	---	---	---	---	---
RX5day	0.273	---	---	---	(2.307)
R10mm	---	---	---	---	---
R95p	---	---	---	---	---

The trends shown in Table 13 indicate a relatively even split between increasing and decreasing. Average annual maximum temperature, average annual minimum temperature, and warm days are all decreasing. Cool days and maximum consecutive five-day precipitation amount are both increasing.

3.5 Jonesboro

Jonesboro's data was analyzed by the full record, and then in intervals. The first interval was twenty years (1910 – 1930), while the remaining three intervals were thirty years each (1930 – 1960, 1960 – 1990, and 1990 – 2020). Jonesboro is one of three cities studied where the data record did not extend back to 1900. The following table shows results of both significance and non-significance.

Table 14. P-values for Jonesboro results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1910 – 2020	**1910 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.39	0.192	0.028 **	0.643
TMIN	0.001 **	0.012 **	0.518	0.163	0.198
TX90p	≤0.001 **	0.772	0.075 *	0.151	0.133
TX10p	0.002 **	0.332	0.784	0.422	0.45
PRCPTOT	0.505	0.245	0.389	0.619	0.271
RX5day	0.9	0.054 *	0.372	0.619	0.086 *
R10mm	0.805	0.573	0.232	0.743	0.933
R95p	0.68	0.467	0.568	0.745	0.028 **

Only the four temperature indices are statistically significant for the full data record. None of the precipitation indices are statistically significant for the full data record. All four of the temperature indices that are statistically significant for the full data record are statistically significant at the 95% confidence level. Six additional results are statistically significant – average annual minimum temperature for the 1910 to 1930 interval, maximum consecutive five-day precipitation amount for the 1910 to 1930 interval, warm days for the 1930 to 1960 interval, average annual maximum temperature for the 1960 to 1990 interval, maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, and very wet days for the 1990 to 2020 interval. Three of the results are statistically significant at the 95% confidence level, and they are average annual minimum temperature for the 1910 to 1930 interval, average annual maximum temperature for the 1960 to 1990 interval, and very wet days for the 1990 to 2020 interval. The remaining three results – maximum consecutive five-day precipitation amount for the 1910 to

1930 interval, warm days for the 1930 to 1960 interval, and maximum consecutive five-day precipitation amount for the 1990 to 2020 interval – are statistically significant at the 90% confidence level.

Table 15. Slope values for Jonesboro results of significance.

	1910 – 2020	1910 – 1930	1930 – 1960	1960 – 1990	1990 – 2020
TMAX	-0.016	---	---	-0.027	---
TMIN	0.009	0.129	---	---	---
TX90p	-0.088	---	-0.152	---	---
TX10p	0.03	---	---	---	---
PRCPTOT	---	---	---	---	---
RX5day	---	-4.563	---	---	1.586
R10mm	---	---	---	---	---
R95p	---	---	---	---	9.058

The trends shown in Table 15 indicate a relatively even split between increasing and decreasing. Average annual maximum temperature and warm days are decreasing, while average annual minimum temperature and cool days are increasing. Maximum consecutive five-day precipitation amount shows a strong decrease during the 1910 to 1930 interval, but the 1990 to 2020 interval shows a steady increase. Likewise, very wet days shows a very strong increase in the 1990 to 2020 interval.

3.6 Rogers

Rogers' data was analyzed by the full record, and then in three intervals between thirty-five and forty years in length (1900 – 1940, 1940 – 1975, and 1981 – 2020). Analyzing by these intervals tricks RClimDex into thinking that there are fewer missing data points, and trends for TX90p and TX10p can be calculated. The following table shows results of both significance and non-significance.

Table 16. P-values for Rogers results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1940**	**1940 – 1975**	**1981 – 2020**
TMAX	≤0.001 **	≤0.001 **	0.544	0.288
TMIN	0.949	0.344	0.513	≤0.001 **
TX90p	N/A	0.001 **	0.229	0.182
TX10p	N/A	0.003 **	0.612	0.994
PRCPTOT	0.036 **	0.276	0.224	0.243
RX5day	0.087 *	0.229	0.509	0.01 **
R10mm	0.058 *	0.964	0.234	0.777
R95p	0.952	0.119	0.182	0.048 **

Only four of the eight climate indices are statistically significant for the full data record, and they are average annual maximum temperature, total annual precipitation, maximum consecutive five-day precipitation amount, and annual number of heavy precipitation days. Average annual maximum temperature and total annual precipitation are statistically significant at the 95% confidence level, and maximum consecutive five-day precipitation amount and annual number of heavy precipitation days are statistically significant at the 90% confidence level. Six additional results are statistically significant, all at the 95% confidence level. These results are the average annual maximum temperature for the 1900 to 1940 interval, warm days for the 1900 to 1940 interval, cool days for the 1900 to 1940 interval, average annual minimum temperature for the

1981 to 2020 interval, maximum consecutive five-day precipitation amount for the 1981 to 2020 interval, and very wet days for the 1981 to 2020 interval.

Table 17. Slope values for Rogers results of significance.

	1900 – 2020	1900 – 1940	1940 – 1975	1981 – 2020
TMAX	-0.014	0.048	---	---
TMIN	---	---	---	0.063
TX90p	N/A	0.245	---	---
TX10p	N/A	-0.125	---	---
PRCPTOT	1.529	---	---	---
RX5day	0.258	---	---	1.979
R10mm	0.041	---	---	---
R95p	---	---	---	5.455

Overall, the trends shown in Table 17 indicate an increase in most indices. The only negative trends are the average annual maximum temperature for the full data record, and cool days for the 1900 to 1940 interval. The strongest increasing trend is very wet days for the 1981 to 2020 interval, followed by the maximum consecutive five-day precipitation amount for the 1981 to 2020 interval and the total annual precipitation for the full data record, respectively.

3.7 Conway

Conway's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, and 1990 – 2020). The following table shows results of both significance and non-significance.

Table 18. P-values for Conway results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.458	0.182	0.742	0.647
TMIN	0.146	0.182	0.073 *	0.122	0.895
TX90p	≤0.001 **	0.679	0.241	0.342	0.172
TX10p	0.005 **	0.366	0.625	0.658	0.871
PRCPTOT	0.344	0.655	0.96	0.514	0.264
RX5day	0.823	0.522	0.113	0.673	0.017 **
R10mm	0.261	0.517	0.924	0.348	0.634
R95p	0.353	0.937	0.452	0.81	0.015 **

Only three of the eight climate indices are statistically significant for the full data record, and they are average annual maximum temperature, warm days, and cool days. All three of these indices are statistically significant at the 95% confidence level. Three additional results are statistically significant, and they are average annual minimum temperature for the 1930 to 1960 interval, maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, and very wet days for the 1990 to 2020 interval. The average annual minimum temperature for the 1930 to 1960 interval is statistically significant at the 90% confidence level, and the maximum consecutive five-day precipitation amount for the 1990 to 2020 interval and very wet days for the 1990 to 2020 interval are statistically significant at the 95% confidence level.

Table 19. Slope values for Conway results of significance.

	1900 – 2020	1900 – 1930	1930 – 1960	1960 – 1990	1990 – 2020
TMAX	-0.01	---	---	---	---
TMIN	---	---	-0.022	---	---
TX90p	-0.057	---	---	---	---
TX10p	0.028	---	---	---	---
PRCPTOT	---	---	---	---	---
RX5day	---	---	---	---	2.678
R10mm	---	---	---	---	---
R95p	---	---	---	---	11.919

The trends shown in Table 19 indicate a relatively even split between increasing and decreasing. Average annual maximum temperature for the full data record, average annual minimum temperature for the 1930 to 1960 interval, and warm days for the full data record are all decreasing. Cool days for the full data record, maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, and very wet days for the 1990 to 2020 interval are all increasing. The strongest increasing trend is very wet days for the 1990 to 2020 interval, with a slope around twelve. The second strongest increasing trend is the maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, with a slope around 3.

3.8 Bentonville

Bentonville's data was analyzed by the full record, and then in intervals. The first interval was seventeen years (1943 – 1960), while the remaining two intervals were thirty years each (1960 – 1990 and 1990 – 2020). Bentonville is one of three cities studied where the data record did not extend back to 1900. The following table shows results of both significance and non-significance.

Table 20. P-values for Bentonville results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1943 – 2020	**1943 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	0.003 **	0.975	0.004 **	0.423
TMIN	≤0.001 **	0.56	0.011 **	≤0.001 **
TX90p	0.016 **	0.829	0.167	0.456
TX10p	0.004 **	0.47	0.01 **	0.621
PRCPTOT	0.137	0.241	0.791	0.469
RX5day	0.073 *	N/A	0.404	0.02 **
R10mm	0.194	0.948	0.71	0.933
R95p	0.265	0.143	0.438	0.085 *

Five of the eight climate indices are statistically significant for the full data record. These indices are average annual maximum temperature, average annual minimum temperature, warm days, cool days, and maximum consecutive five-day precipitation amount. All four of the temperature indices that are statistically significant for the full data record are statistically significant at the 95% confidence level. The maximum consecutive five-day precipitation amount for the full data record is statistically significant at the 90% confidence level. Six additional results are statistically significant; five are statistically significant at the 95% confidence level and one is statistically significant at the 90% confidence level. The five results that are statistically significant at the 95% confidence level are average annual maximum temperature for the 1960 to 1990 interval, average annual minimum temperature for the 1960 to 1990 interval, cool days for the 1960 to 1990 interval, average annual minimum temperature for the 1990 to 2020 interval, and the maximum consecutive five-day precipitation amount for the 1990 to 2020 interval. The result that is statistically significant at the 90% confidence level is very wet days at the 1990 to 2020 interval.

The average annual minimum temperature has the highest number of statistically significant results, with three significant trends: the full data record, the 1960 to 1990 interval, and the 1990 to 2020 interval.

Table 21. Slope values for Bentonville results of significance.

	1943 – 2020	**1943 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	-0.016	---	-0.056	---
TMIN	0.019	---	-0.045	0.061
TX90p	-0.078	---	---	---
TX10p	0.058	---	0.216	---
PRCPTOT	---	---	---	---
RX5day	0.526	N/A	---	2.785
R10mm	---	---	---	---
R95p	---	---	---	6.851

The trends shown in Table 21 indicate a relatively even split between increasing and decreasing. The average annual maximum temperature for the full data record and for the 1960 to 1990 interval are decreasing, the average annual minimum temperature for the 1960 to 1990 interval is decreasing, and warm days for the full data record is decreasing. The strongest increasing trend is very wet days for the 1990 to 2020 interval, with a slope around seven. The second strongest increasing trend is maximum consecutive five-day precipitation amount for the 1990 to 2020 interval, with a slope around three.

3.9 Pine Bluff

Pine Bluff's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, and 1990 – 2020). The following table shows results of both significance and non-significance.

Table 22. P-values for Pine Bluff results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.003 **	0.033 **	0.065 *	0.975
TMIN	0.007 **	0.001 **	≤0.001 **	0.158	0.092 *
TX90p	≤0.001 **	0.041 **	0.346	0.2	0.81
TX10p	0.005 **	0.021 **	0.193	0.205	0.727
PRCPTOT	0.755	0.14	0.848	0.01 **	0.72
RX5day	0.211	0.559	0.16	0.547	0.458
R10mm	0.524	0.541	0.655	0.033 **	0.616
R95p	0.797	0.176	0.89	0.243	0.555

Only four of the eight climate indices are statistically significant for the full data record, and they are all four of the temperature indices and none of the precipitation indices. All four of the temperature indices are statistically significant at the 95% confidence level. All four of the temperature indices are statistically significant at the 95% confidence level for the 1900 to 1930 interval, as well. Six additional results are statistically significant, four at the 95% confidence level and two at the 90% confidence level. Average annual maximum temperature for the 1930 to 1960 interval, average annual minimum temperature for the 1930 to 1960 interval, total annual precipitation for the 1960 to 1990 interval, and annual number of heavy precipitation days for the 1960 to 1990 interval are statistically significant at the 95% confidence level. Average annual maximum temperature for the 1960 to 1990 interval and average annual minimum temperature for the 1990 to 2020 interval are statistically significant at the 90% confidence level.

Table 23. Slope values for Pine Bluff results of significance.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	-0.013	0.063	-0.038	-0.029	---
TMIN	0.006	0.063	-0.066	---	-0.022
TX90p	-0.08	0.267	---	--	---
TX10p	0.027	-0.188	---	---	---
PRCPTOT	---	---	---	15.929	---
RX5day	---	---	---	---	---
R10mm	---	---	---	0.382	---
R95p	---	---	---	---	---

The trends shown in Table 23 indicate a relatively even split between increasing and decreasing. Average annual maximum temperature and warm days are decreasing, for the full data record. Average annual minimum temperature and cool days are increasing, for the full data record. For the 1900 to 1930 interval, average annual maximum temperature, average annual minimum temperature, and warm days are all increasing, while cool days are decreasing. Average annual maximum temperature is decreasing on the 1930 to 1960 interval and on the 1960 to 1990 interval. Average annual minimum temperature is decreasing on the 1930 to 1960 interval and the 1990 to 2020 interval. The strongest increasing trend is total annual precipitation for the 1960 to 1990 interval, with a slope around sixteen. The second strongest increasing trend is annual number of heavy precipitation days for the 1960 to 1990 interval.

3.10 Hot Springs

Hot Springs' data was analyzed by the full record, and then in thirty-year intervals (1930 – 1960, 1960 – 1990, and 1990 – 2020). Hot Springs is one of three cities studied where the data record did not extend back to 1900. The following table shows results of both significance and non-significance.

Table 24. P-values for Hot Springs results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1930 – 2020	**1930 – 1960**	**1960 – 1990**	**1990 - 2020**
TMAX	≤0.001 **	0.628	0.539	0.208
TMIN	≤0.001 **	0.677	≤0.001 **	0.001 **
TX90p	0.006 **	0.432	0.05 *	0.332
TX10p	≤0.001 **	0.865	0.17	0.551
PRCPTOT	0.981	0.764	0.556	0.707
RX5day	0.386	0.144	0.791	0.959
R10mm	0.218	0.566	0.218	0.868
R95p	0.405	0.963	0.562	0.894

Only four of the eight climate indices are statistically significant for the full data record, and they are all four of the temperature indices and none of the precipitation indices. All four temperature indices are statistically significant at the 95% confidence level. There are three additional results that are statistically significant, and they are average annual minimum temperature for the 1960 to 1990 interval, warm days for the 1960 to 1990 interval, and average annual minimum temperature for the 1990 to 2020 interval. Warm days for the 1960 to 1990 interval is statistically significant at the 90% confidence level, and the average annual minimum temperature for the 1960 to 1990 and 1990 to 2020 intervals are statistically significant at the 95% confidence level. None of the precipitation indices are statistically significant, at either the full record or on any of the thirty-year intervals.

The average annual minimum temperature has the highest number of statistically significant results, with three significant trends: the full data record, the 1960 to 1990 interval, and the 1990 to 2020 interval.

Table 25. Slope values for Hot Springs results of significance.

	1930 – 2020	**1930 – 1960**	**1960 – 1990**	**1990 - 2020**
TMAX	-0.016	---	---	---
TMIN	-0.018	---	-0.067	0.054
TX90p	-0.067	---	0.191	---
TX10p	0.062	---	---	---
PRCPTOT	---	---	---	---
RX5day	---	---	---	---
R10mm	---	---	---	---
R95p	---	---	---	---

The trends shown in Table 25 indicate that the majority of the results are decreasing. Average annual maximum temperature, average annual minimum temperature, and warm days, all for the full data record, are decreasing. Average annual minimum temperature for the 1960 to 1990 interval is decreasing. Average annual minimum temperature for the 1990 to 2020 interval is increasing. Warm days for the 1960 to 1990 interval are increasing. Since none of the precipitation indices are statistically significant, there are no trends shown in Table 24.

3.11 Texarkana

Texarkana's data was analyzed by the full record, and then in thirty-year intervals (1900 – 1930, 1930 – 1960, 1960 – 1990, and 1990 – 2020). The following table shows results of both significance and non-significance.

Table 26. P-values for Texarkana results of significance and of non-significance, for all eight climate indices. (*) denotes a significant result at α = 0.10, and (**) denotes a significant result at α = 0.05.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	≤0.001 **	0.083 *	0.001 **	0.913	0.533
TMIN	0.051 *	0.422	0.001 **	0.271	0.451
TX90p	≤0.001 **	0.029 **	0.004 **	0.804	0.249
TX10p	≤0.001 **	0.214	0.006 **	0.722	0.89
PRCPTOT	0.335	0.999	0.376	0.926	0.796
RX5day	0.666	0.246	0.367	0.296	0.981
R10mm	0.138	0.583	0.868	0.531	0.172
R95p	0.128	0.897	0.1 *	0.001 **	0.1 *

Only four of the eight climate indices are statistically significant for the full data record, and they are all four of the temperature indices, and none of the precipitation indices. Average annual maximum temperature, warm days, and cool days are all statistically significant at the 95%

confidence level for the full data record. Average annual minimum temperature for the full data record is statistically significant at the 90% confidence level. All four temperature indices are statistically significant at the 95% confidence level for the 1930 to 1960 interval. Five additional results are statistically significant, with two at the 95% confidence level and three at the 90% confidence level. Warm days for the 1900 to 1930 interval and very wet days for the 1960 to 1990 interval are statistically significant at the 95% confidence level. Average annual maximum temperature for the 1900 to 1930 interval, very wet days for the 1930 to 1960 interval, and very wet days for the 1990 to 2020 interval are statistically significant at the 90% confidence level.

Table 27. Slope values for Texarkana results of significance.

	1900 – 2020	**1900 – 1930**	**1930 – 1960**	**1960 – 1990**	**1990 – 2020**
TMAX	-0.013	0.04	-0.066	---	---
TMIN	0.004	---	0.042	---	---
TX90p	-0.068	0.252	-0.366	---	---
TX10p	0.038	---	0.218	---	---
PRCPTOT	---	---	---	---	---
RX5day	---	---	---	---	---
R10mm	---	---	---	---	---
R95p	---	---	-5.421	-9.604	7.372

The trends shown in Table 27 indicate a relatively even split between increasing and decreasing. The trends of note are the intervals for very wet days. From 1930 to 1960, very wet days are decreasing with a slope around five. From 1960 to 1990, very wet days are decreasing with a slope around ten. From 1990 to 2020, very wet days are increasing with a slope around seven.

Chapter 4: Discussion and Conclusions

4.1 Discussion

4.1.1 Study Shortcomings

The majority of the shortcomings of this study can be traced to the software program used for analysis. By using RClimDex only, additional analyses were not examined. This study does not take into account seasonal variations in precipitation and temperature, as RClimDex analyzes data on an annual basis. Analyzing the data by season would pinpoint if the rainy season has shifted over time, and would determine seasonal patterns in temperature (Feng *et al.*, 2016). Another shortcoming of this study is the lack of disentanglement to determine what percentage of the warming is due to urban heat island effect, rather than global heating due to climate change (Zhao *et al.*, 2014). This particular challenge could be overcome by analyzing rural stations in the state and examining the rate of temperature increase over time and comparing it to the urban sites analyzed in this study. However, it has been established that the urban stations in Arkansas do not have continuous data for long records of time, so the chances of rural stations in Arkansas having continuous data for long records of time are slim. Therefore, urban heat island effect would have to be analyzed another way.

RClimDex does not account for data nonstationarity, and as such, the forcing of linear regression on the data could lead to spurious regression. When examining the data from a purely statistical point of view, linear least squares is not an appropriate method for analyzing time-series data (Diez, Barr and Cetinkaya-Rundel, 2015). However, linear least squares regression is the method programmed into RClimDex. Additionally, RClimDex calculates basic statistics (such as average, standard deviation, skewness, etc.), but does not get into descriptive statistics (such as stationarity, homogeneity, periodicity, and noise). RClimDex calculates a trend value based on linear least squares and weighted linear regression, but this value is not as descriptive as a Mann-Kendall trend or Spearman's rank correlation trend (Repel *et al.*, 2020).

4.1.2 Future Research

An additional hypothesis that could be explored is the connection between the increase in frequency of high-intensity precipitation events and urban flooding (Gertz, Davies and Black, 2019; National Academies of Science Engineering and Medicine, 2019). If it is discovered that there is a strong correlation between high-intensity precipitation events and urban flooding in the state of Arkansas, then these trends would support the update of stormwater infrastructure and the implementation of low impact design and green infrastructure. Considering the results of a 2019 study that showed that most of the stormwater infrastructure in the United States was obsolete, proving a connection between the increase in frequency of high-precipitation events and urban flooding could provide the justification to local and state governments that have been reluctant to overhaul their infrastructure (Wright, Bosma and Lopez-Cantu, 2019).

However, examining precipitation frequency and accumulation is not enough to form a complete picture of changes in high-intensity precipitation events and changes in urban flooding. Additional variables that could be studied include the rate of city development and urbanization and the rate of population growth. The rate of population growth analysis determines how much stress is being placed on water resources each consecutive year, and works hand-in-hand with city development (i.e., as the population grows, more infrastructure is built). The rate of city development and urbanization analysis determines how many impervious surfaces are being constructed each year, which increase runoff and decrease infiltration. Northwest Arkansas (where Fayetteville, Bentonville, and Rogers are located) is one of the fastest growing areas in the United States (Gascon and Varley, 2015; McCann, 2020). With the steady increase in population, and the need for more housing and wider roads, a comprehensive study examining the variables of high-intensity precipitation events, urban flooding, rate of population growth, and rate of urbanization would be invaluable to this region, and other regions like it in the United States.

Projection modeling, or modeling what future precipitation patterns and frequencies will look like, could be built on this project, using the historical analyses as a baseline. Global circulation models often require historical data as an initial input to help calibrate the equations for various warming scenarios. Any changes in infrastructure mentioned in the prior paragraphs would be reactive, based on analysis of past data. If projection modeling of these variables was conducted for these study sites, any changes in infrastructure would be proactive, rather than reactive.

4.2 Conclusions

Null hypothesis one states that the frequency of high-intensity precipitation events has not increased in urban areas in Arkansas over the past 100+ years. The statistically significant results show that Little Rock, Fort Smith, Fayetteville, Rogers, and Bentonville have all had increases in the frequency of high-precipitation events over the last 100+ years. The statistically significant results show that Jonesboro, Conway, Pine Bluff, and Texarkana have all had increases in the frequency of high-precipitation events over the last 30 years, but not over the last 100+ years. Hot Springs has no statistically significant precipitation trends. Therefore, based on the statistically significant results, null hypothesis one is rejected.

Null hypothesis two states that the frequency of high-intensity precipitation events has not increased in urban areas in Arkansas that are located in the Gulf Coastal Plain. The urban areas located in the Gulf Coastal Plain include Little Rock, Jonesboro, Pine Bluff, Hot Springs, and Texarkana. The statistically significant results for Little Rock, Jonesboro, Pine Bluff, and Texarkana show an increase in the frequency of high-intensity precipitation events, ranging from the last thirty years to the past 100+ years. Hot Springs has no statistically significant precipitation trends. Therefore, based on the statistically significant results, null hypothesis two is rejected.

Null hypothesis three states that the frequency of high-intensity precipitation events has not increased in urban areas in Arkansas that are located in the Interior Highlands. The urban areas included in the Interior Highlands include Fort Smith, Fayetteville, Rogers, Conway, and Bentonville. The statistically significant results for Fort Smith, Fayetteville, Rogers, Conway, and Bentonville show an increase in the frequency of high-intensity precipitation events, ranging from the last thirty years to the past 100+ years. Therefore, based on the statistically significant results, null hypothesis three is rejected.

While all three of the null hypotheses are rejected, the hypothesis with the most uncertainty is the first null hypothesis. While nine of the ten cities studied show an increase in high-intensity precipitation events, four of those nine cities show a statistically significant increase only in the last thirty years. It can be concluded with high confidence that the frequency of high-intensity precipitation events is increasing in urban areas in the state of Arkansas and in particular, within the area of Arkansas known as the Interior Highlands. The cities with the largest statistically significant increases in frequency of high-intensity precipitation events are the cities most likely to have issues with urban flooding.

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Appendices

Appendix A: Study Location Maps

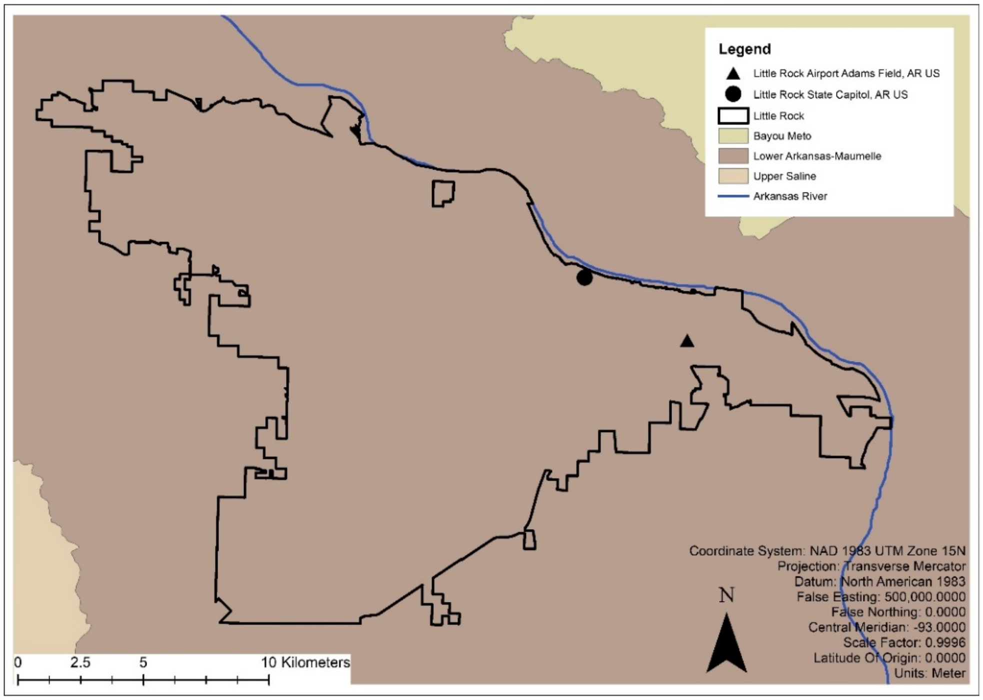

Figure 5. Little Rock city limits, data collection locations, and HUC-8 sub-basins.

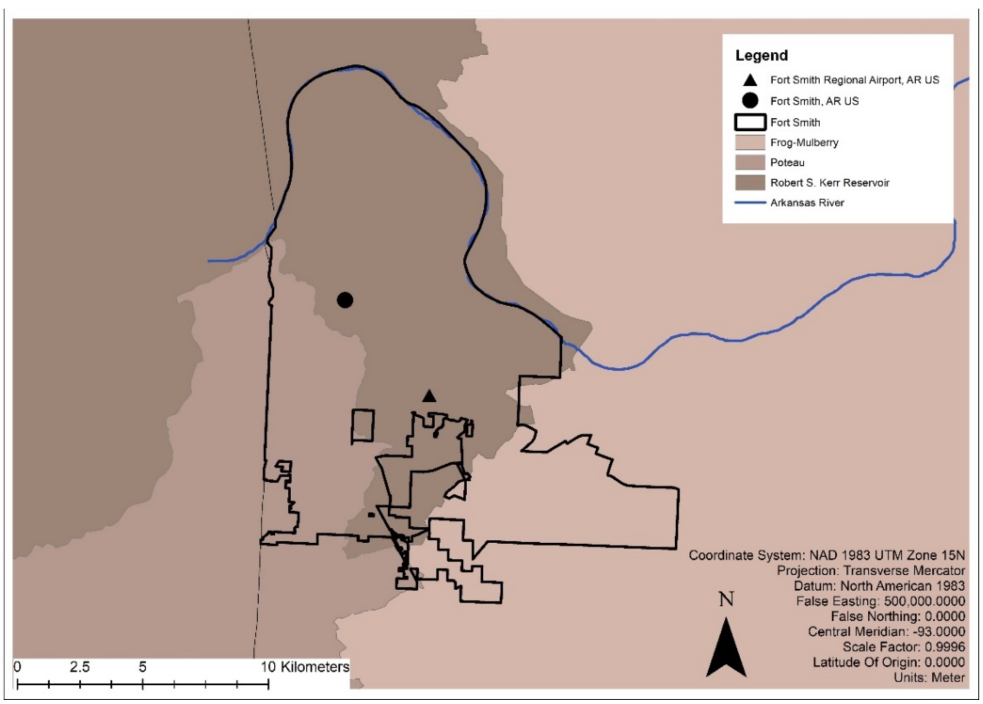

Figure 6. Fort Smith city limits, data collection locations, and HUC-8 sub-basins.

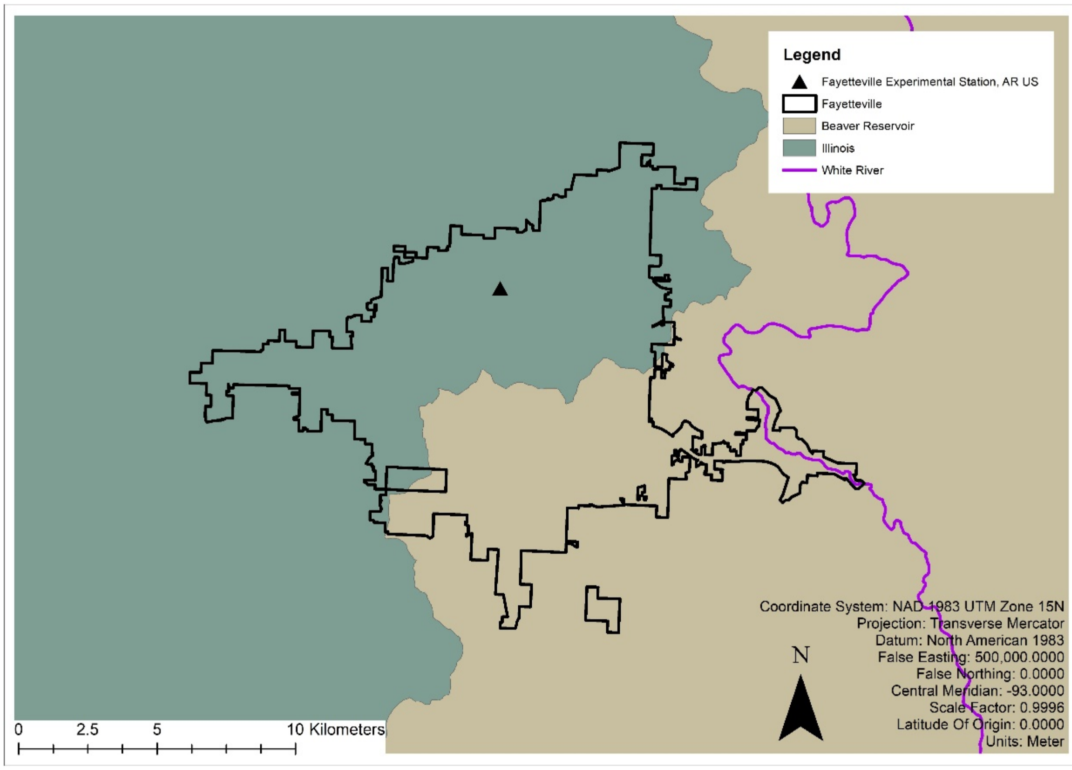

Figure 7. Fayetteville city limits, data collection locations, and HUC-8 sub-basins.

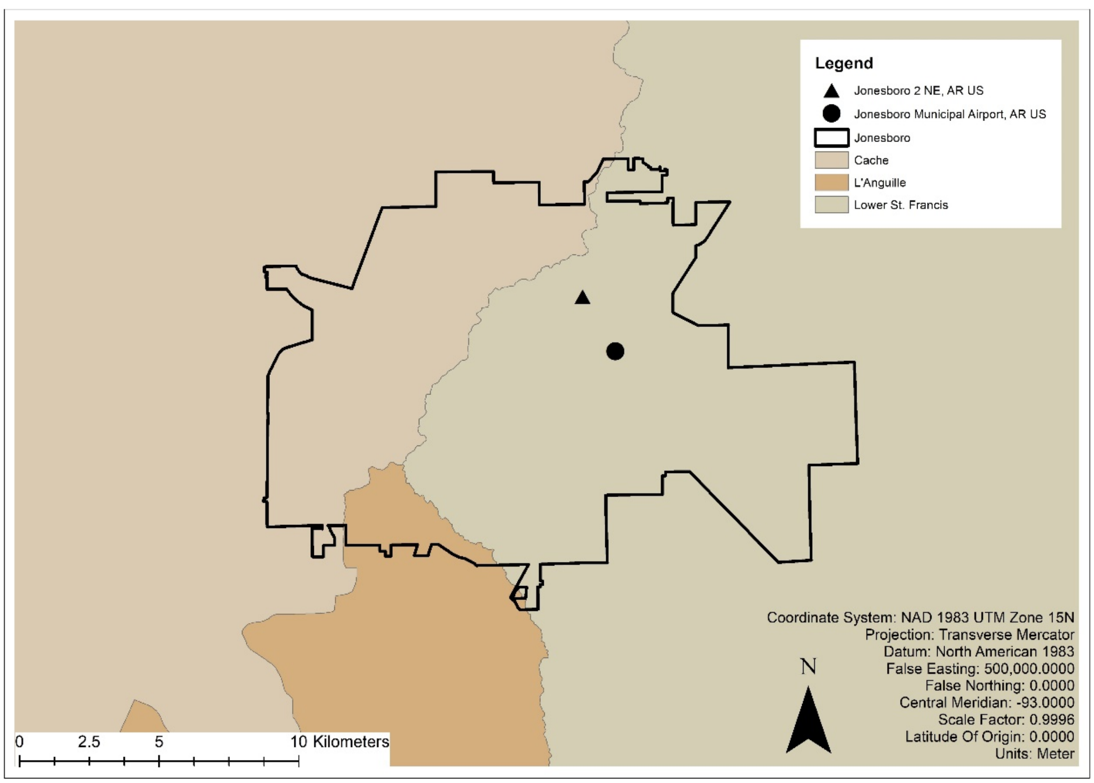

Figure 8. Jonesboro city limits, data collection locations, and HUC-8 sub-basins.

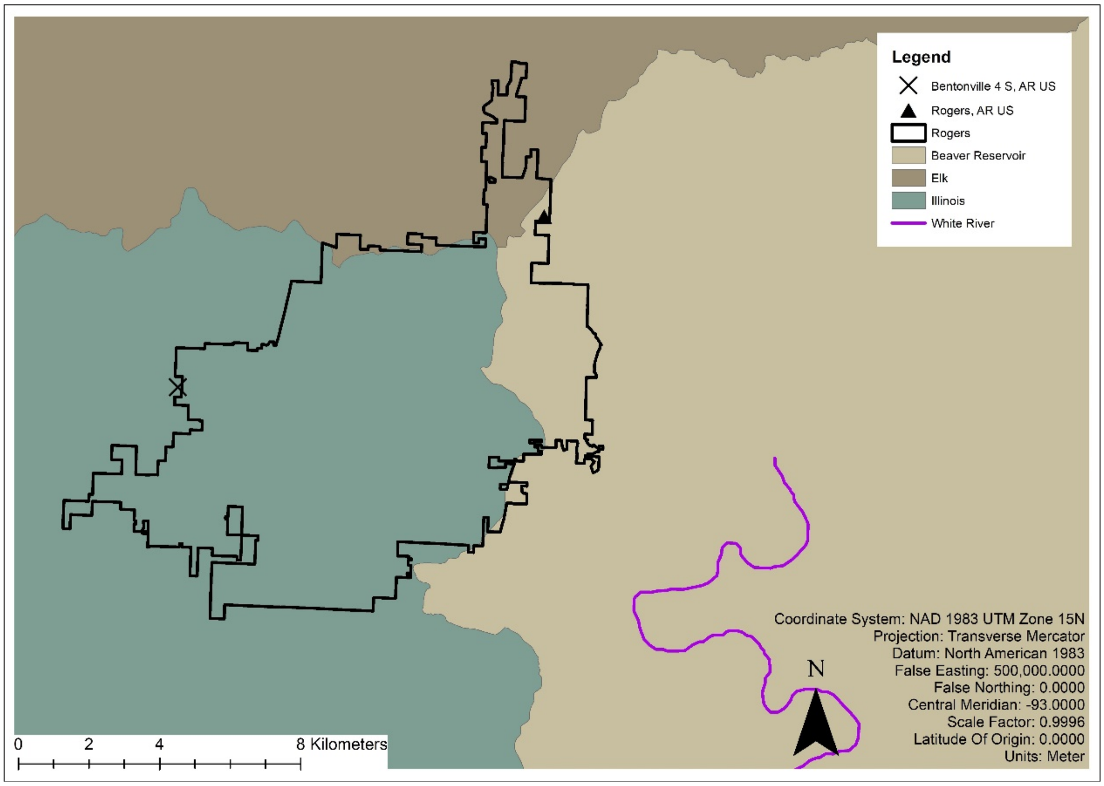

Figure 9. Rogers city limits, data collection locations, and HUC-8 sub-basins.

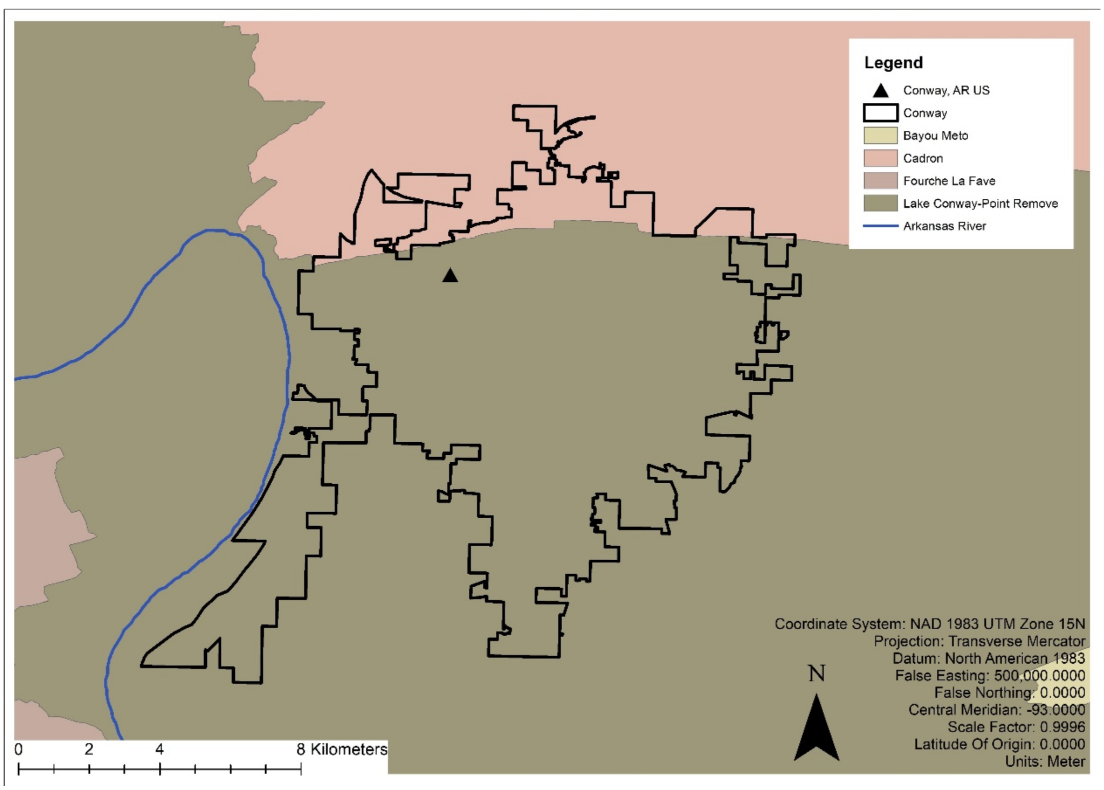

Figure 10. Conway city limits, data collection locations, and HUC-8 sub-basins.

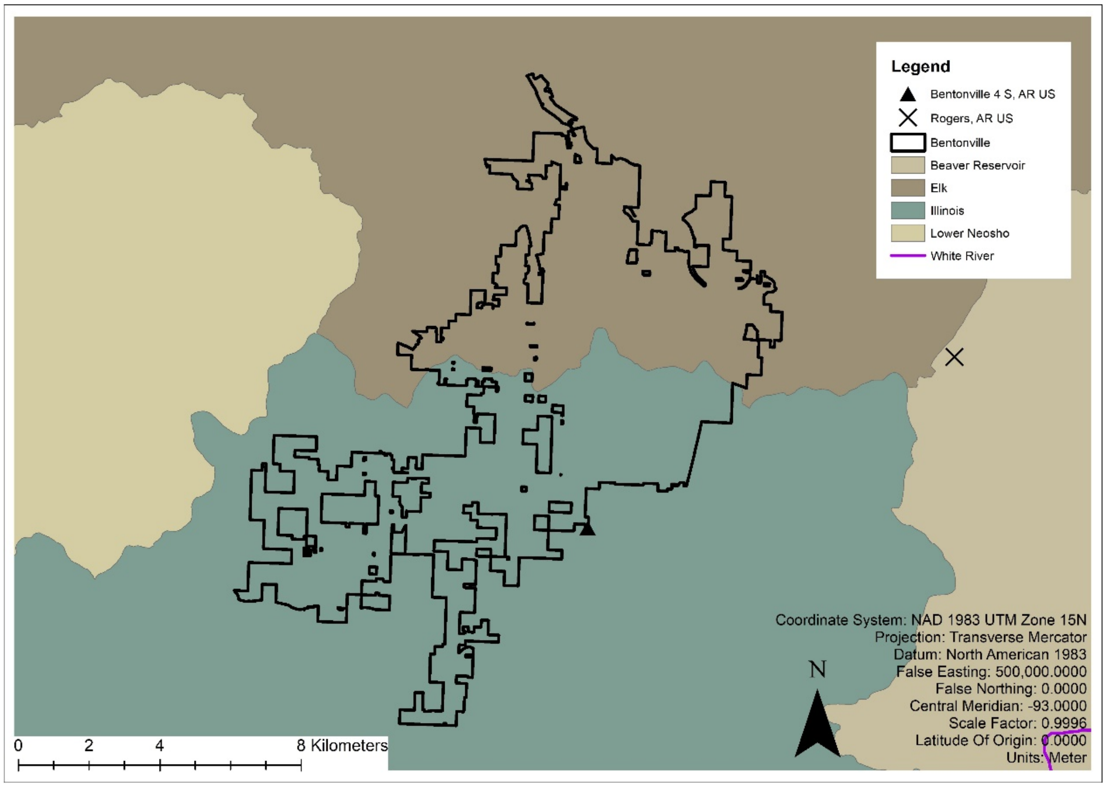

Figure 11. Bentonville city limits, data collection locations, and HUC-8 sub-basins.

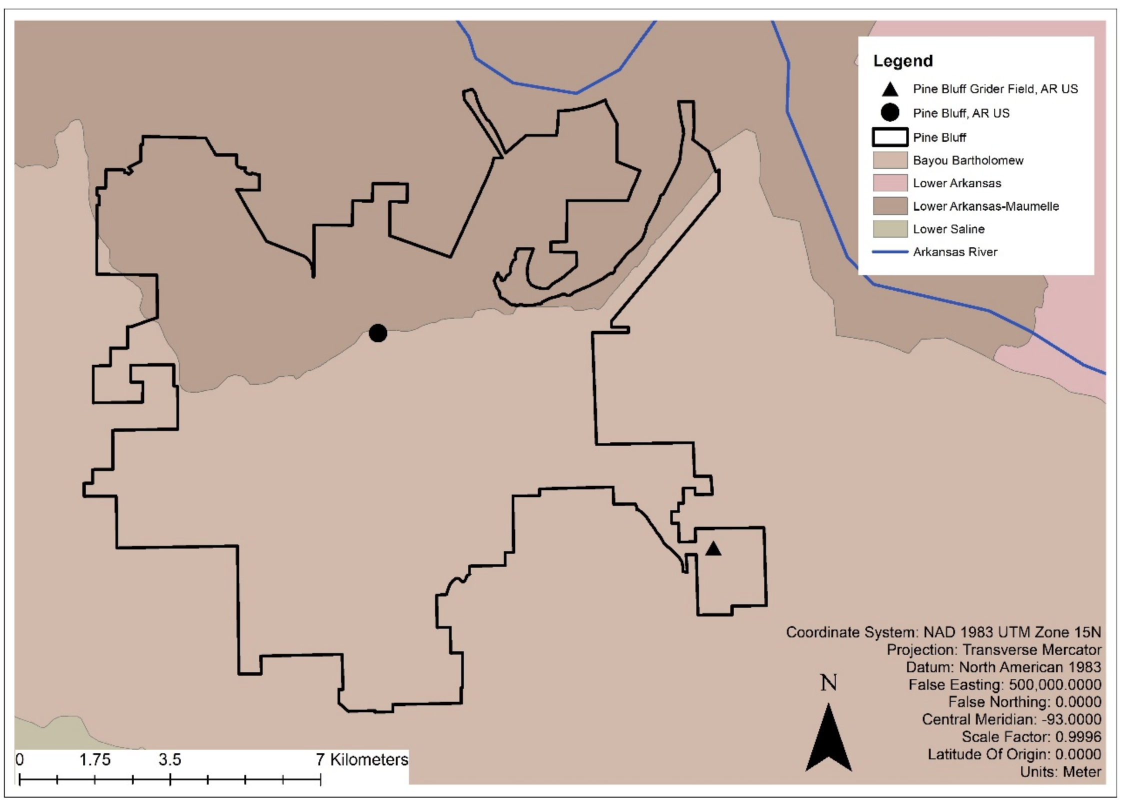

Figure 12. Pine Bluff city limits, data collection locations, and HUC-8 sub-basins.

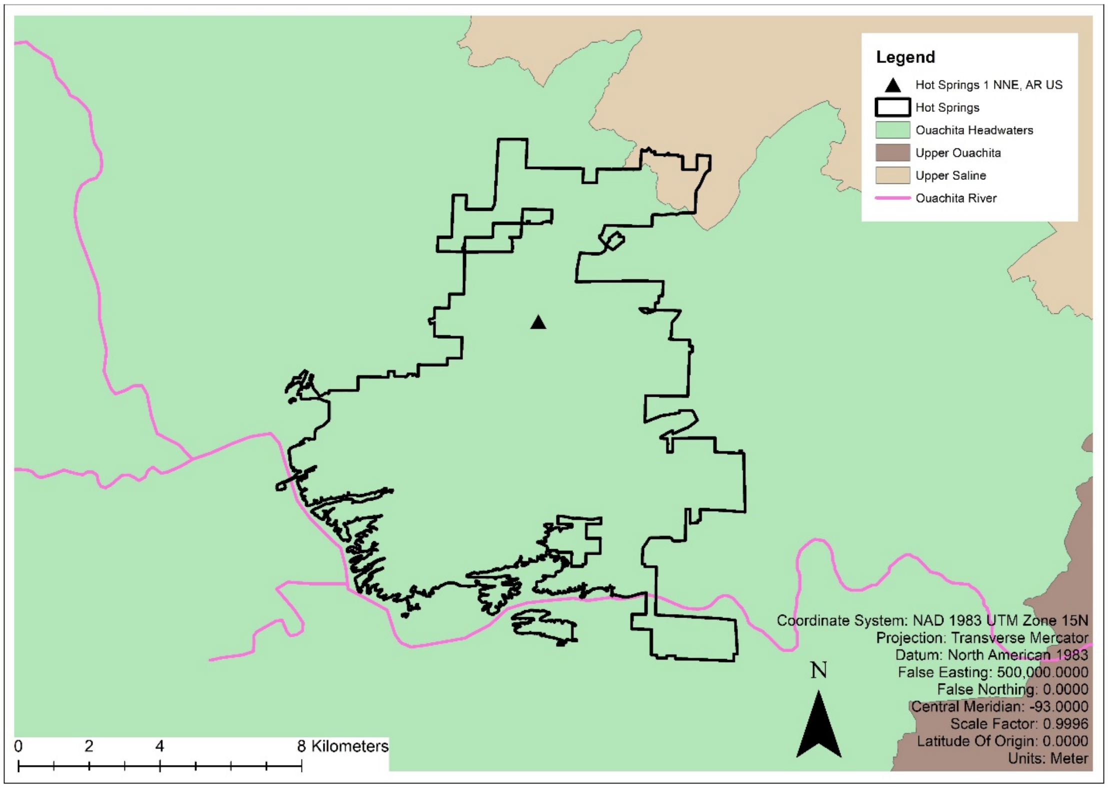

Figure 13. Hot Springs city limits, data collection locations, and HUC-8 sub-basins.

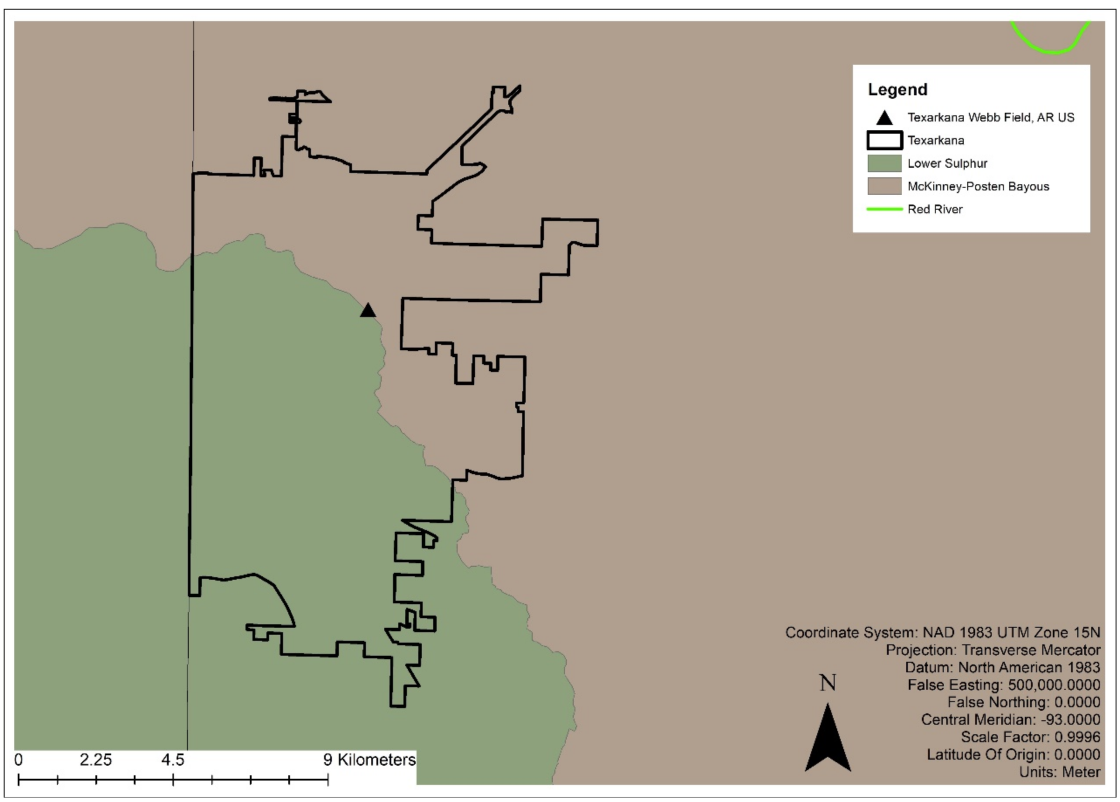

Figure 14. Texarkana city limits, data collection locations, and HUC-8 sub-basins.

Appendix B: Additional ArcGIS Maps

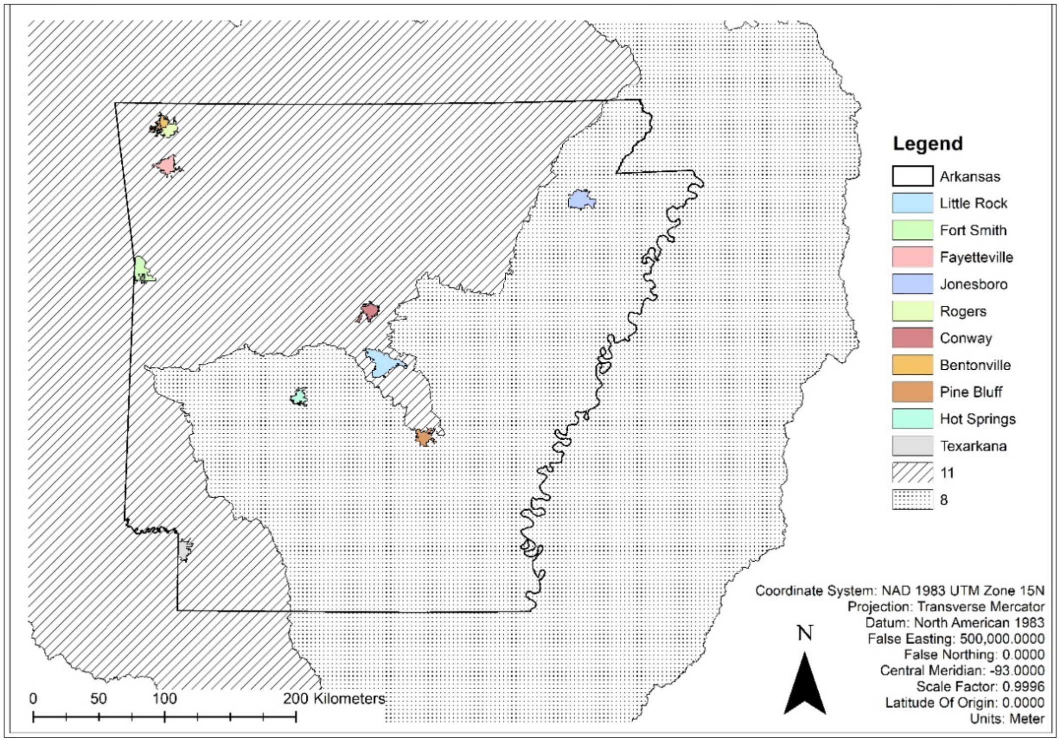

Figure 15. Study locations within two of the major water resource regions of the United States.

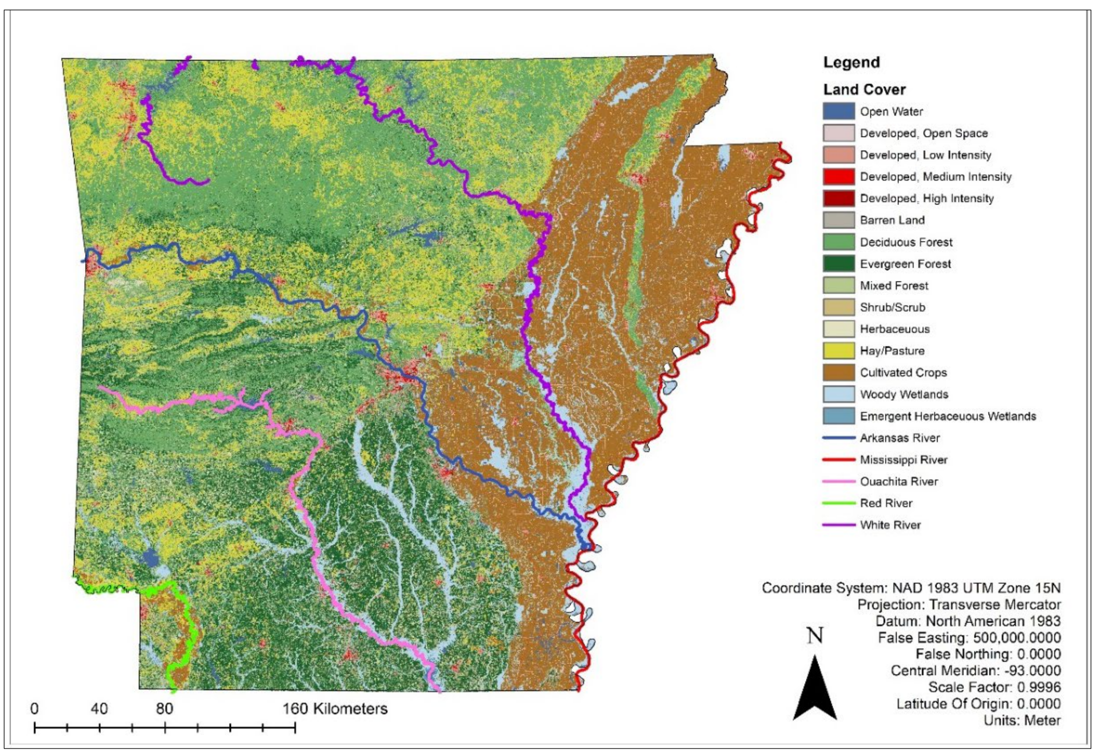

Figure 16. Arkansas land cover with major rivers.

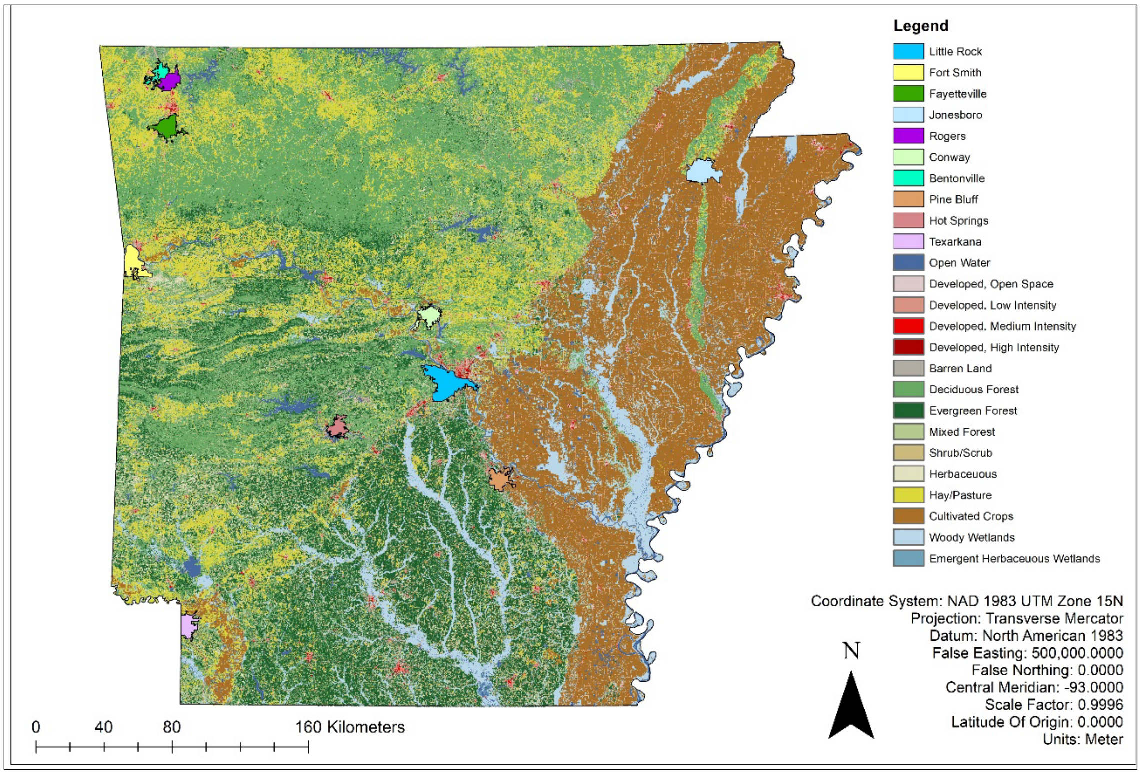

Figure 17. Arkansas land cover with study locations.

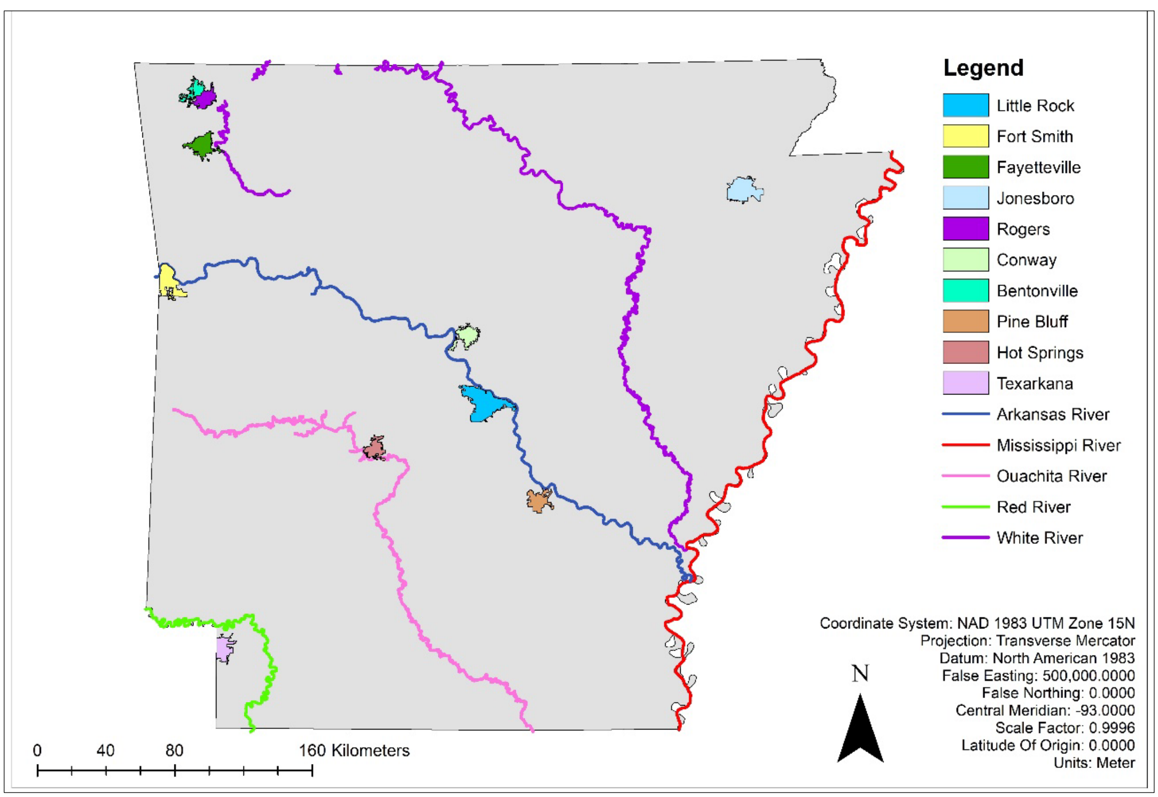

Figure 18. Arkansas major rivers and study locations.

Appendix C: Additional Graphs

As aforementioned in Section 2.1, RClimDex has a couple of visualization bugs, including the multiplication of the actual R^2 value by one hundred, and displaying p-values smaller than 0.001 as zero. The figures included in this appendix have <u>not</u> had the visualization errors corrected, but the errors are consistent across every graph in this appendix.

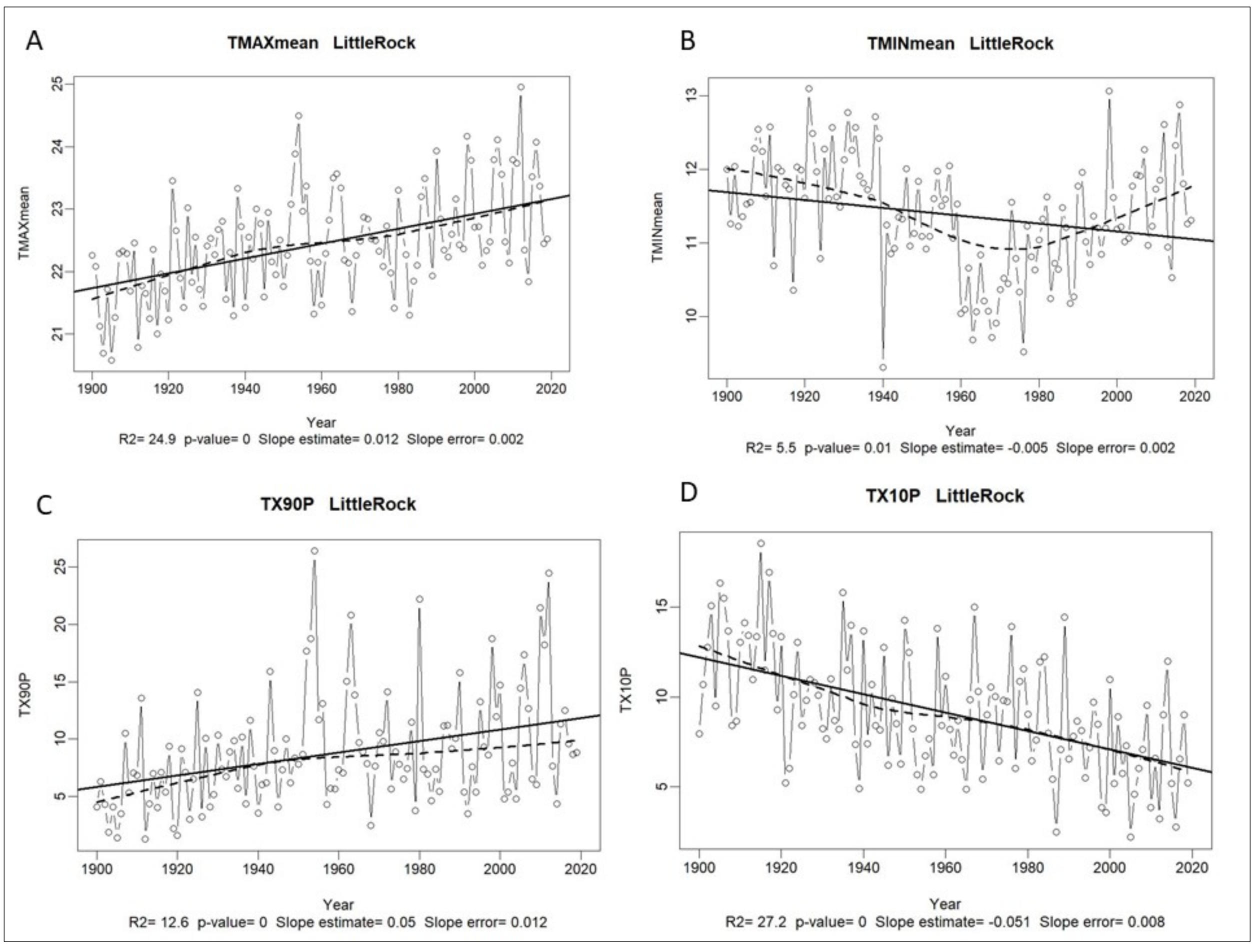

Figure 19. Little Rock temperature indices for the full data record.

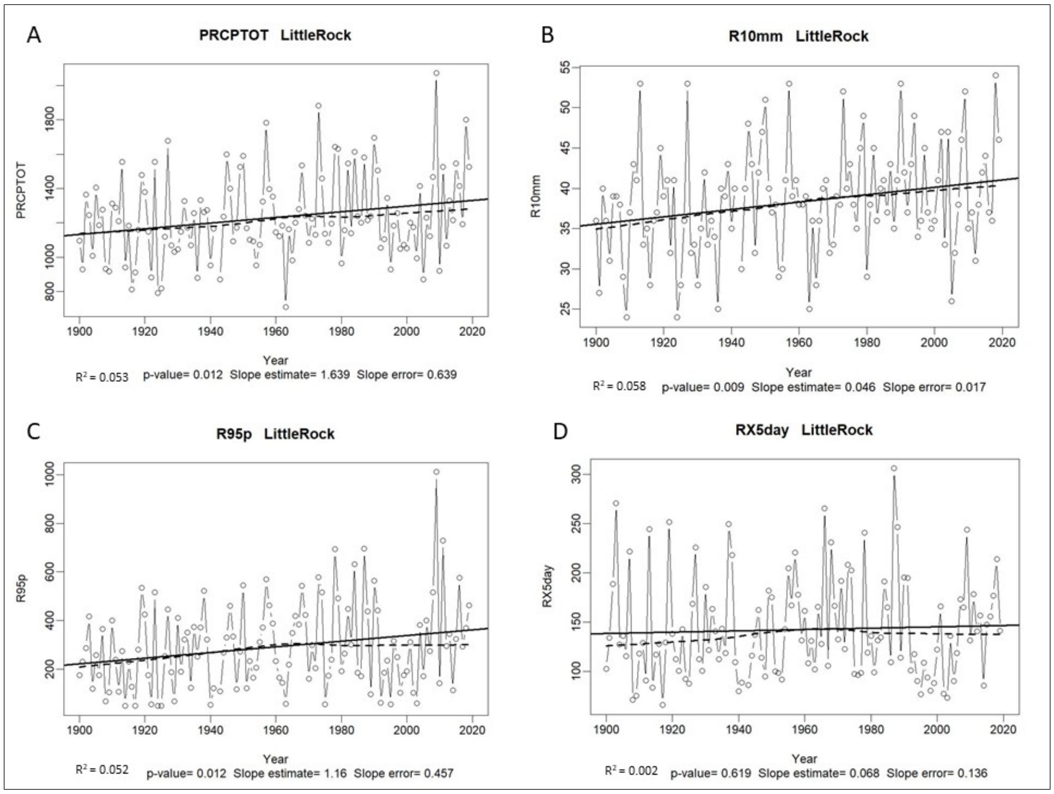

Figure 20. Little Rock precipitation indices for the full data record.

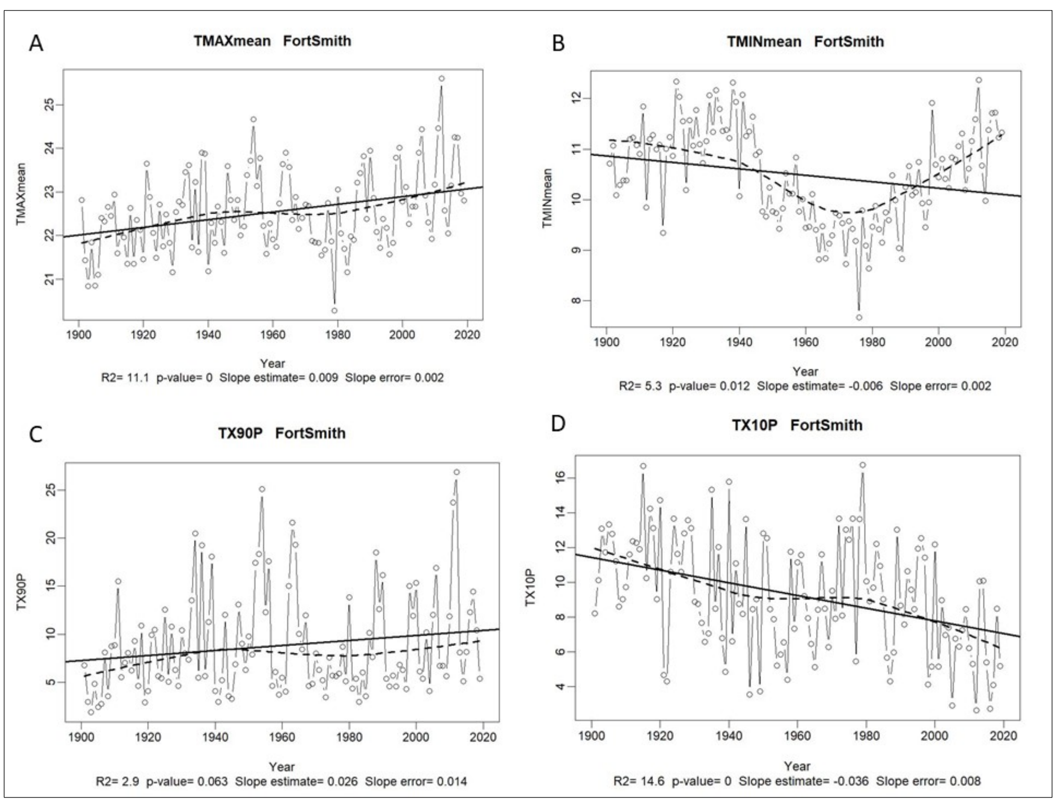

Figure 21. Fort Smith temperature indices for the full data record.

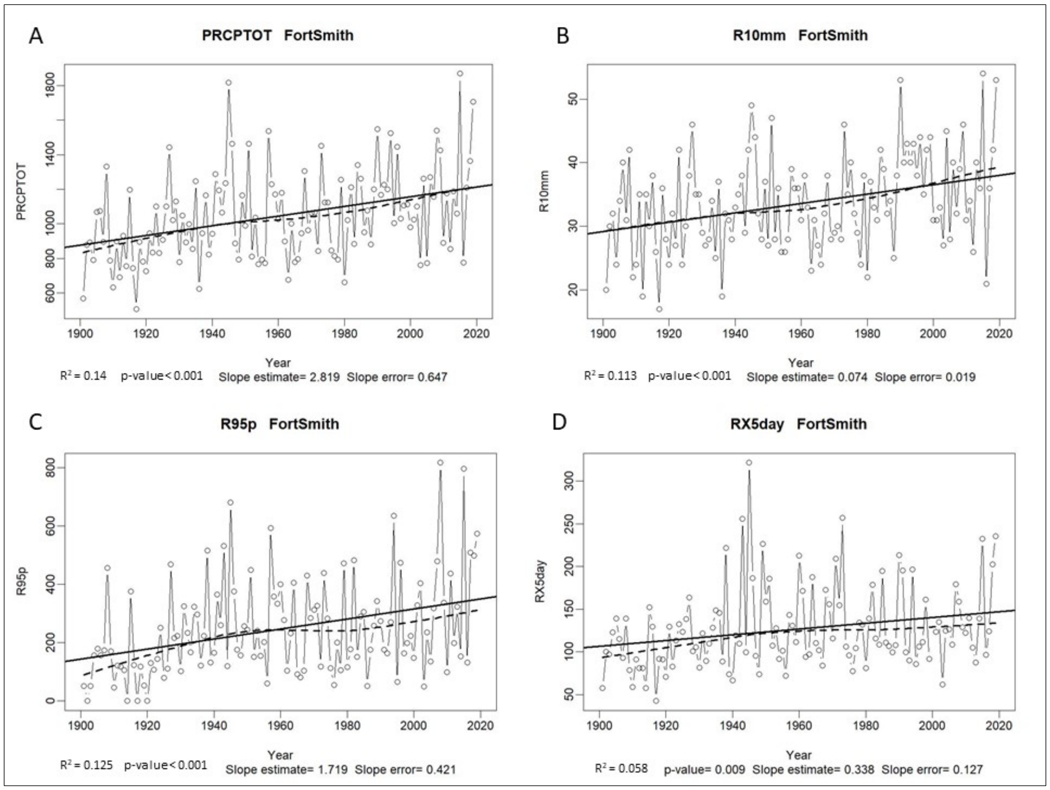

Figure 22. Fort Smith precipitation indices for the full data record.

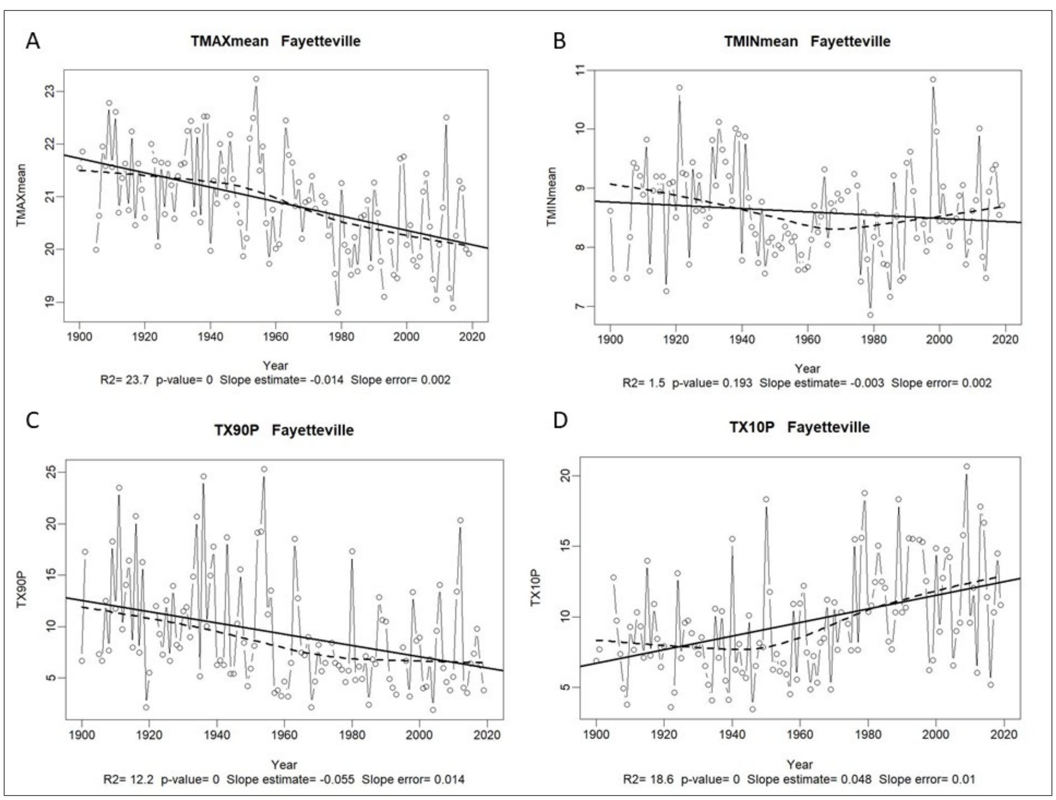

Figure 23. Fayetteville temperature indices for the full data record.

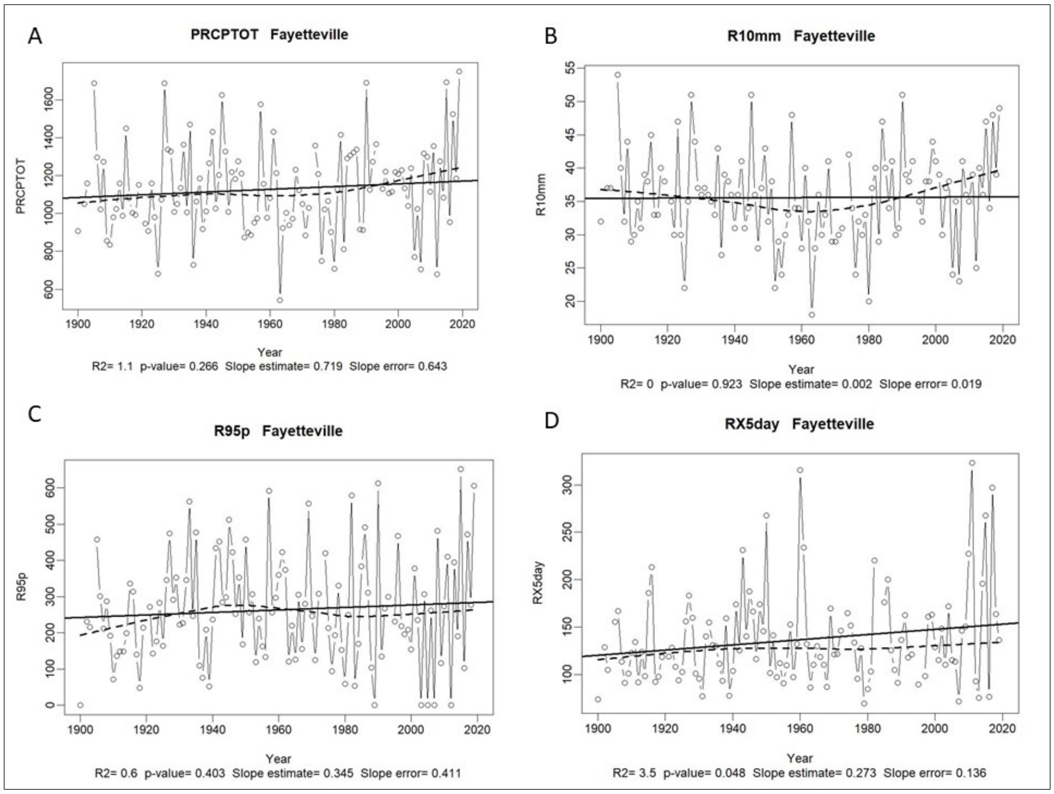

Figure 24. Fayetteville precipitation indices for the full data record.

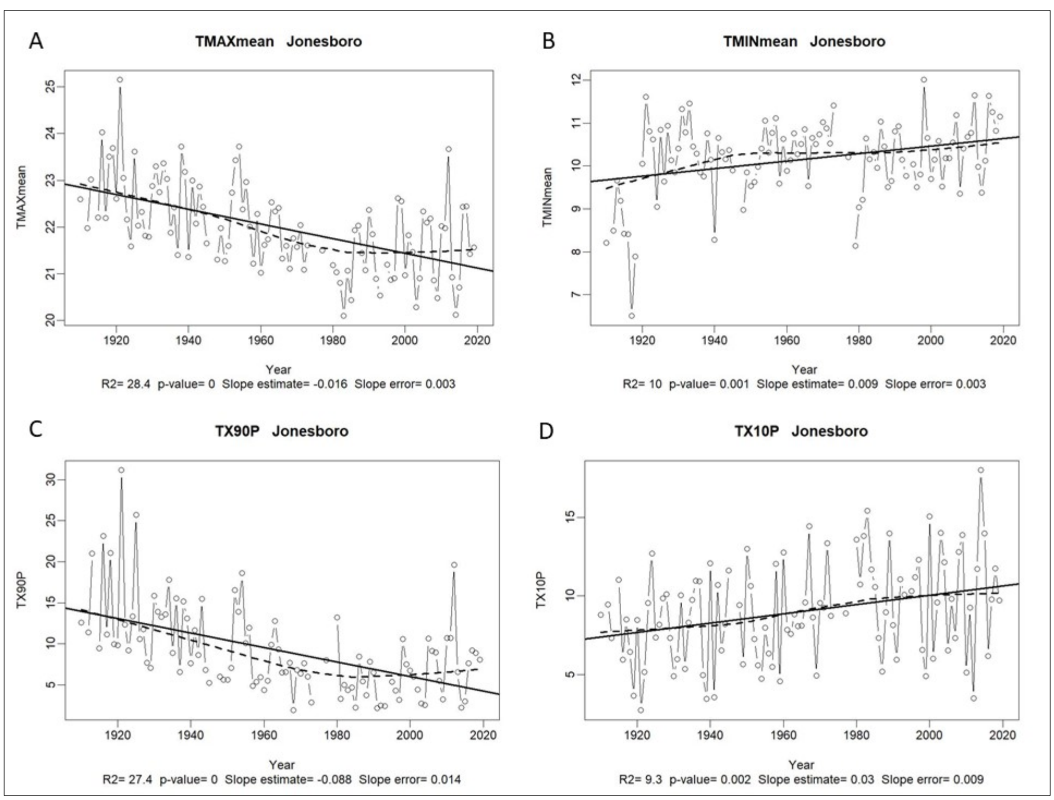

Figure 25. Jonesboro temperature indices for the full data record.

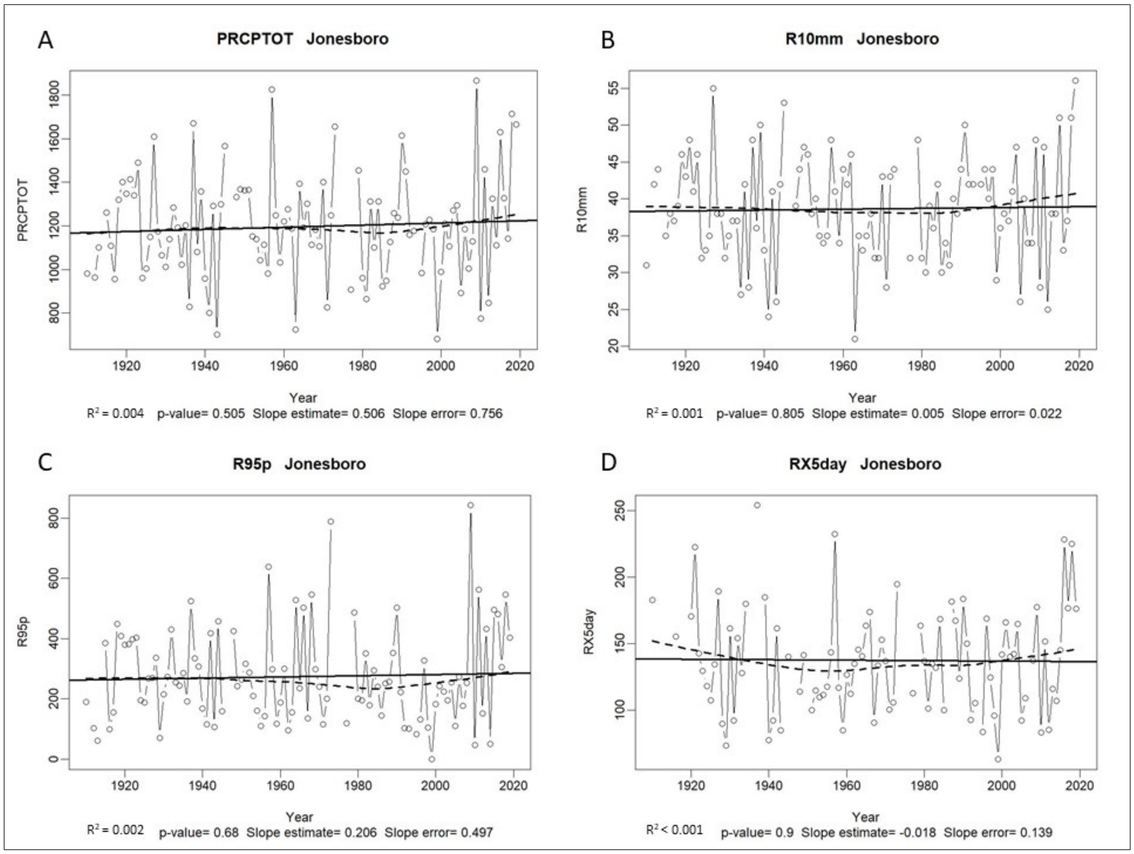

Figure 26. Jonesboro temperature indices for the full data record.

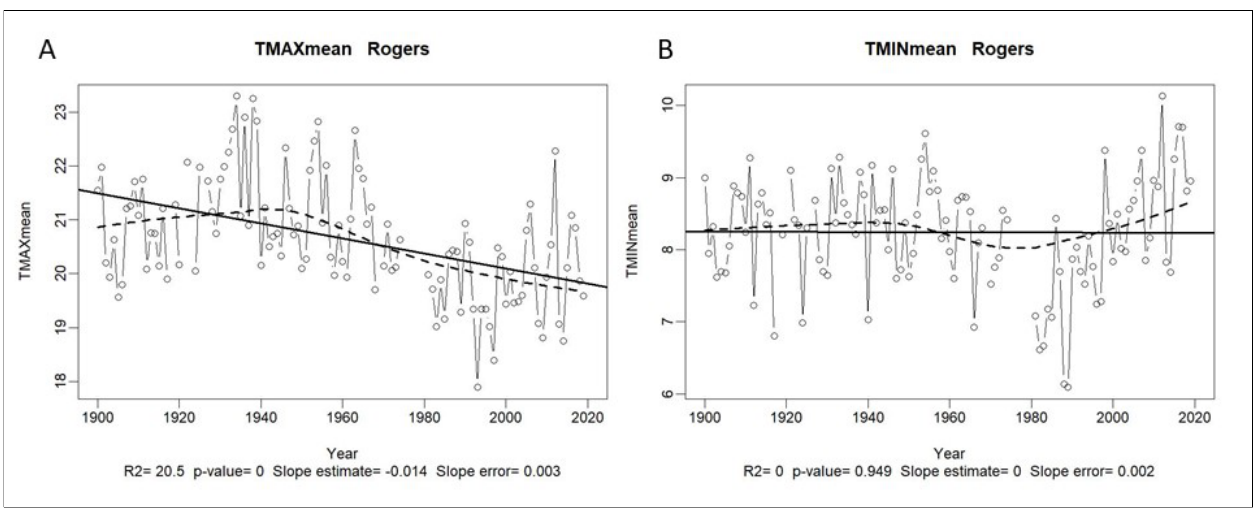

Figure 27. Rogers temperature indices for the full data record.

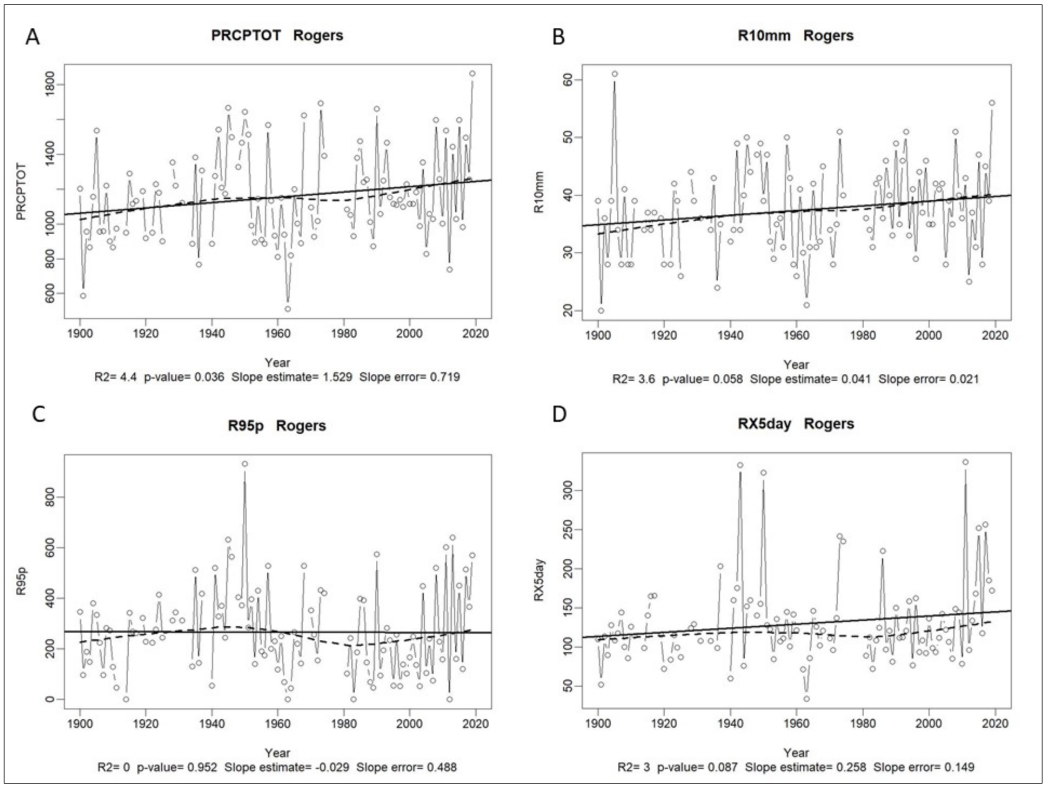

Figure 28. Jonesboro precipitation indices for full data record.

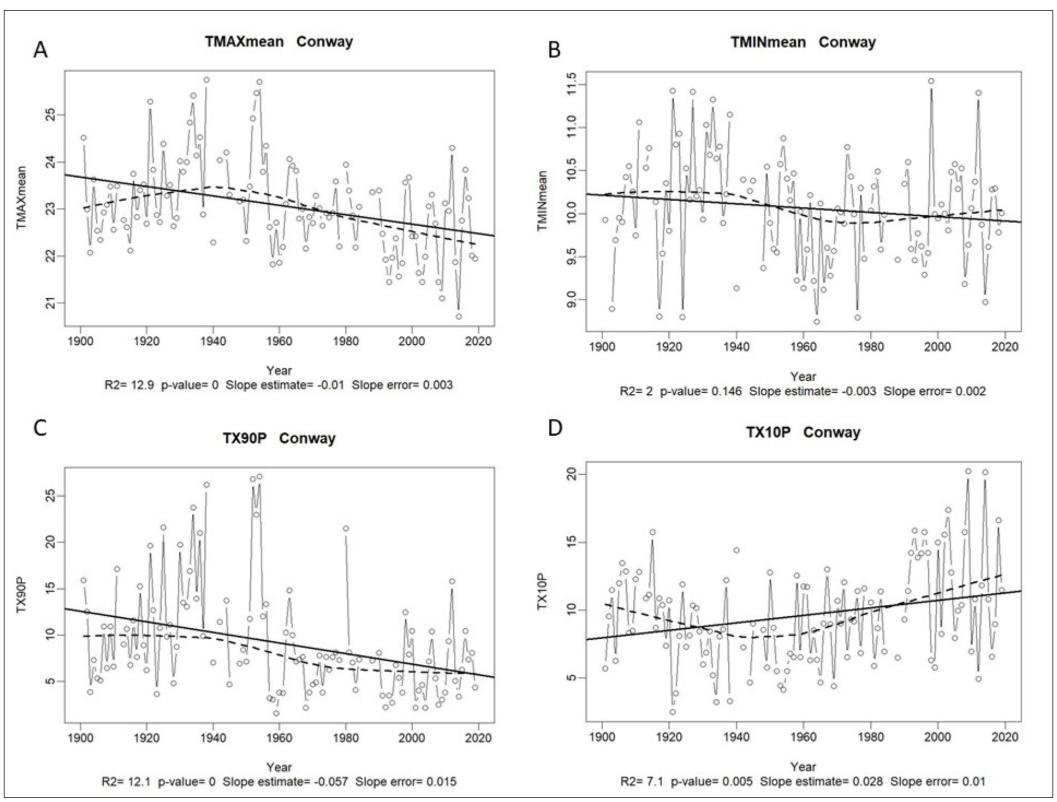

Figure 29. Conway temperature indices for the full data record.

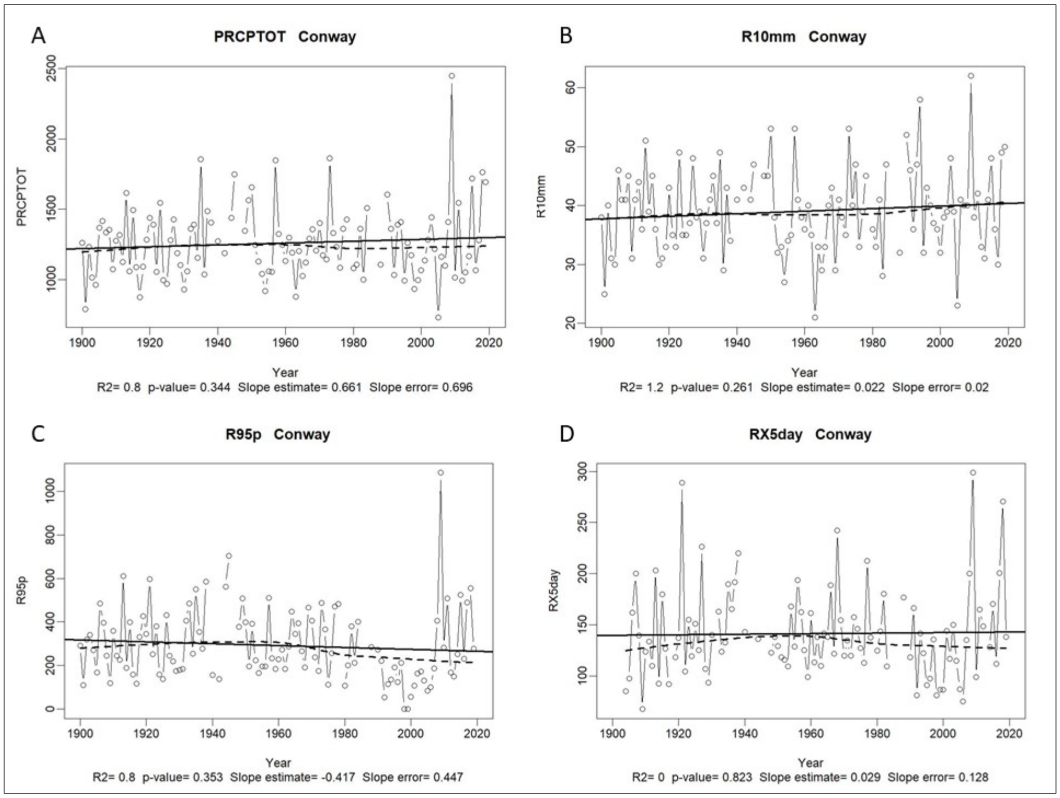

Figure 30. Conway precipitation indices for the full data record.

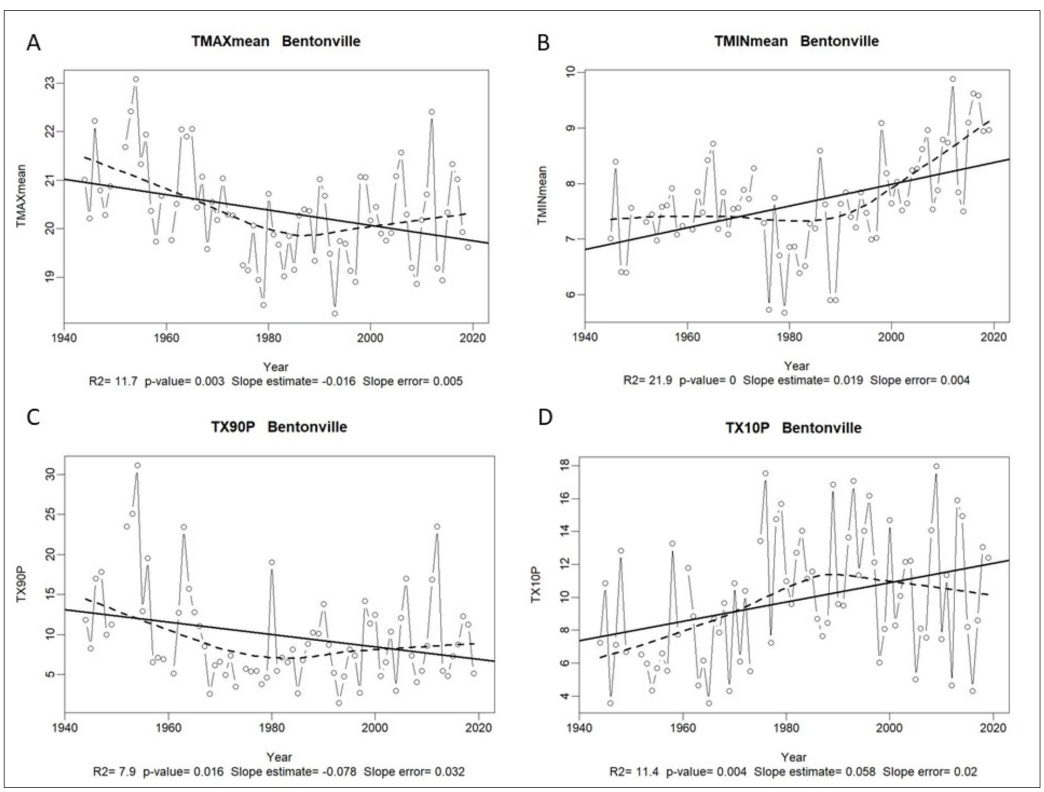

Figure 31. Bentonville temperature indices for the full data record.

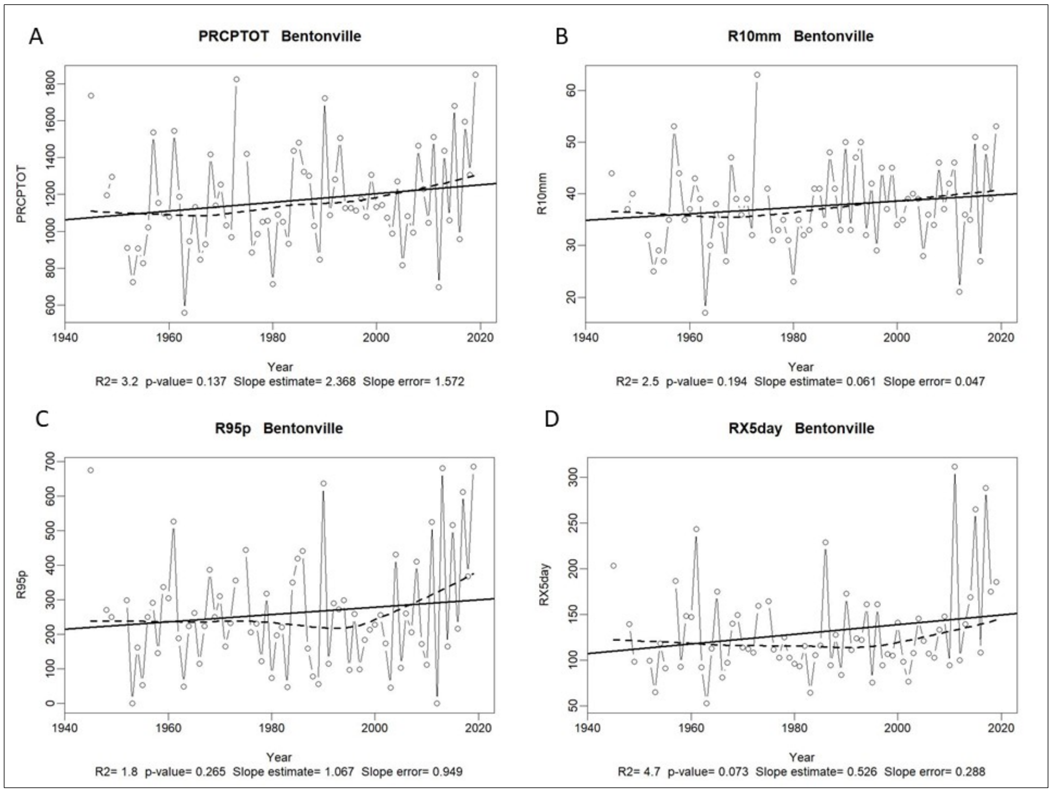

Figure 32. Bentonville precipitation indices for the full data record.

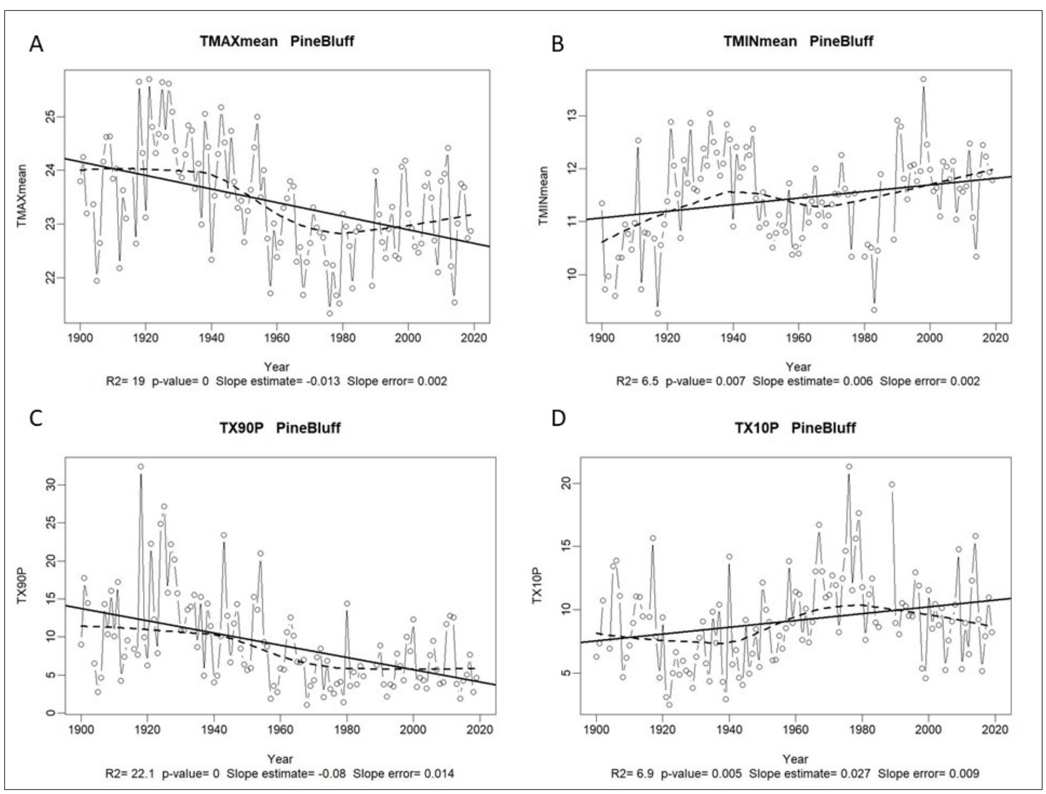

Figure 33. Pine Bluff temperature indices for the full data record.

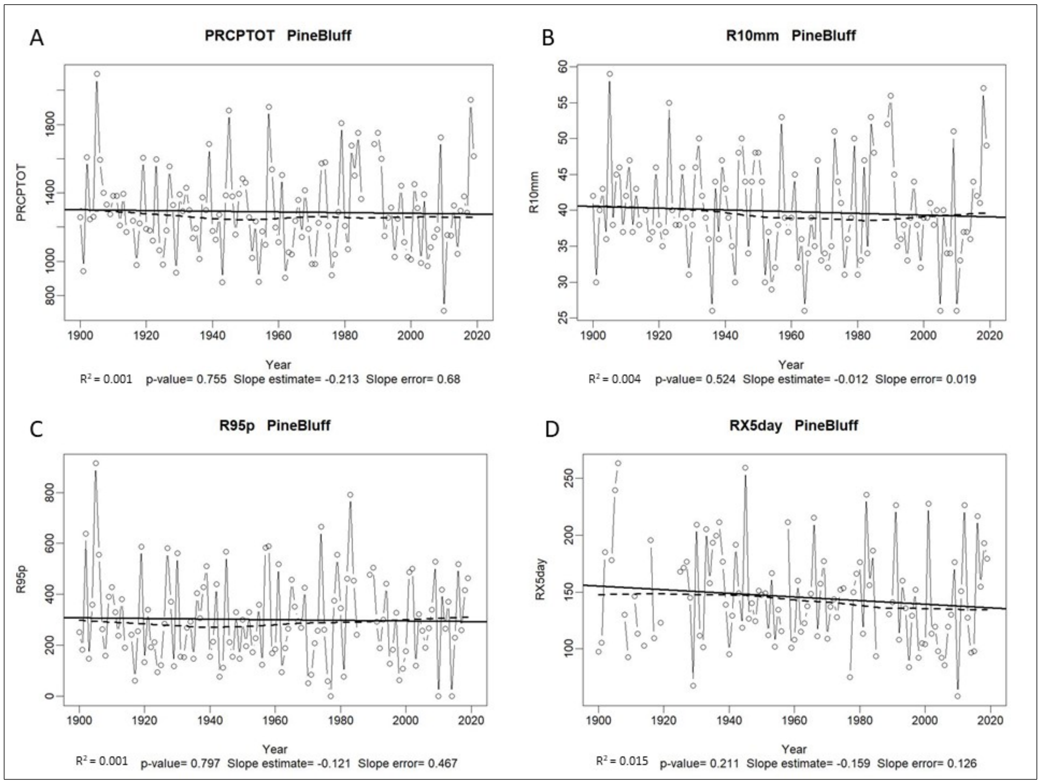

Figure 34. Pine Bluff precipitation indices for the full data record.

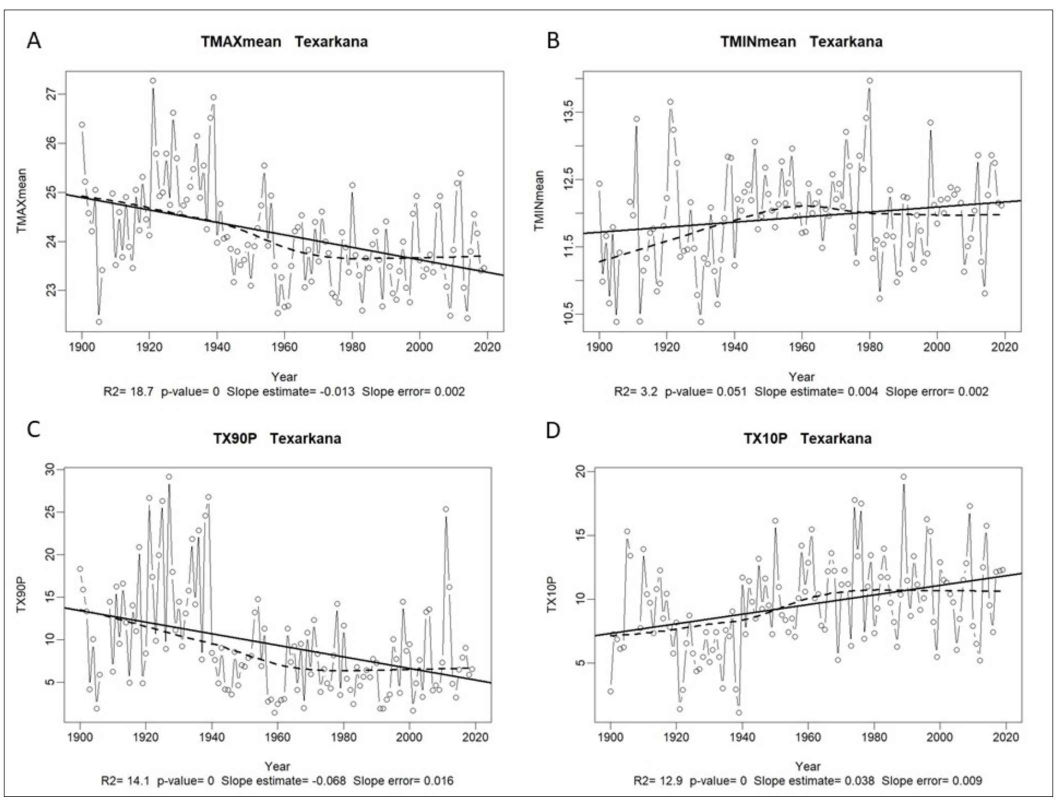

Figure 35. Texarkana temperature indices for the full data record.

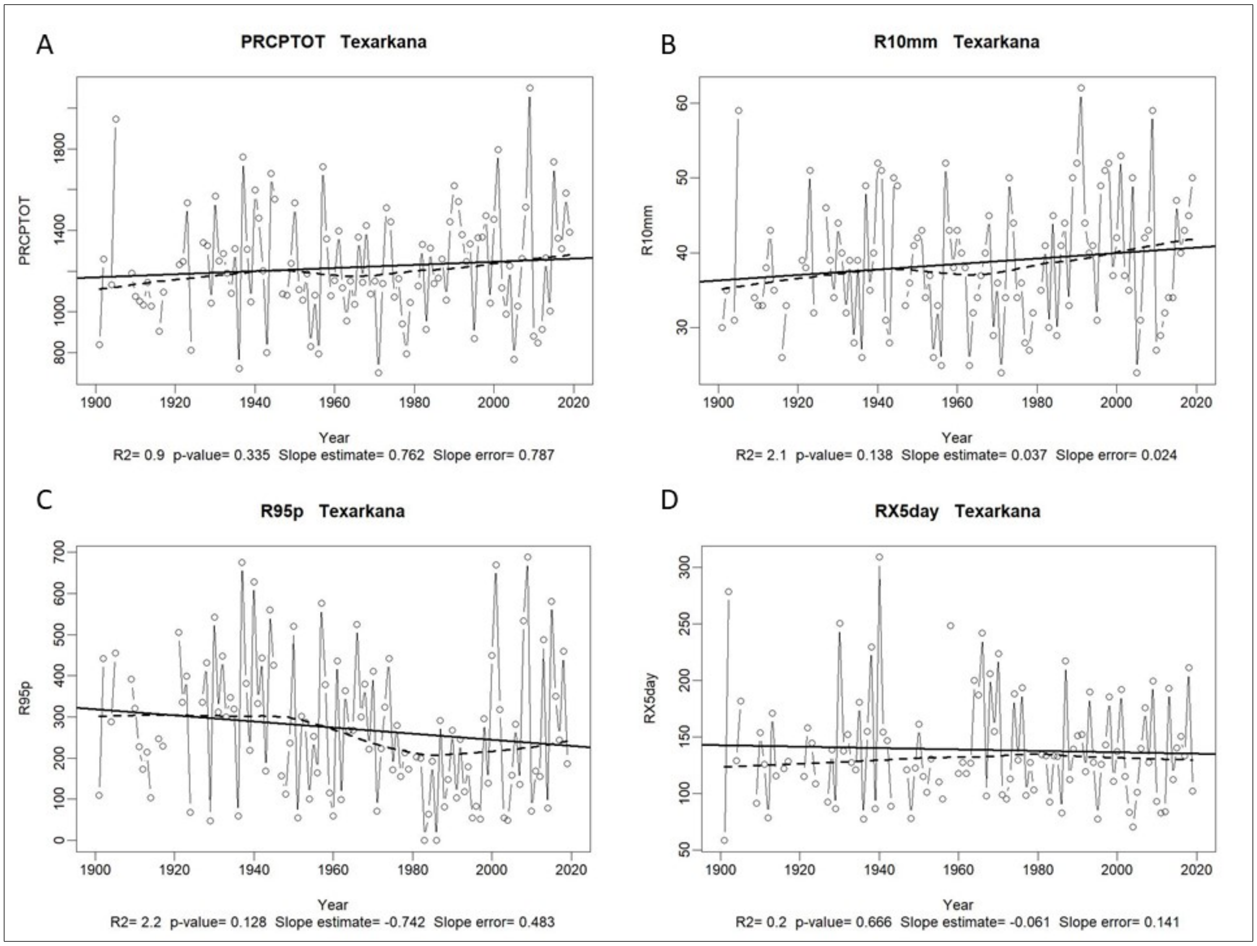

Figure 36. Texarkana precipitation indices for the full data record.